April 30, 2020

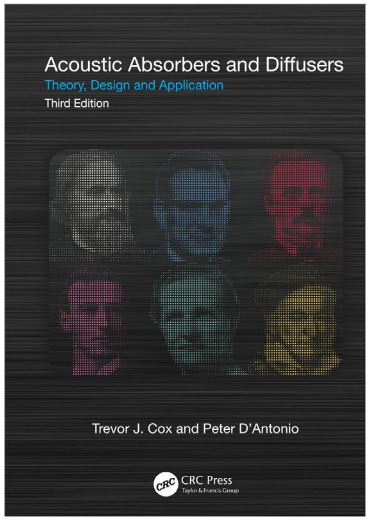
Sound Absorptive Materials
Basics and Future Trends

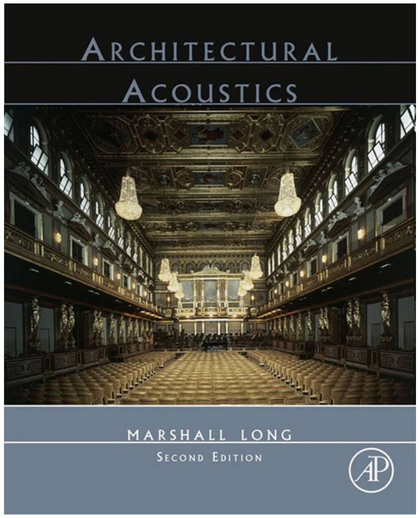
Vibro-Acoustics Consortium Web Meeting

University of Kentucky

References

1. T. J. Cox and P. D'Antonio, *Acoustic Absorbers and Diffusers: Theory, Design and Application*, 3rd Edition, CRC Press, Boca Raton, FL (2017).
2. M. Long, *Architectural Acoustics*, 2nd Edition, Elsevier, Kidlington, Oxford (2014).





Overview

- Porous Absorbers Overview
- Porous Absorbers Property Determination
- Porous Absorbers Basics for Designers
- Porous Absorbers Compressed
- Porous Absorbers Layered
- Reactive Absorbers Overview
- Reactive Absorbers Example

Porous Absorbers Overview

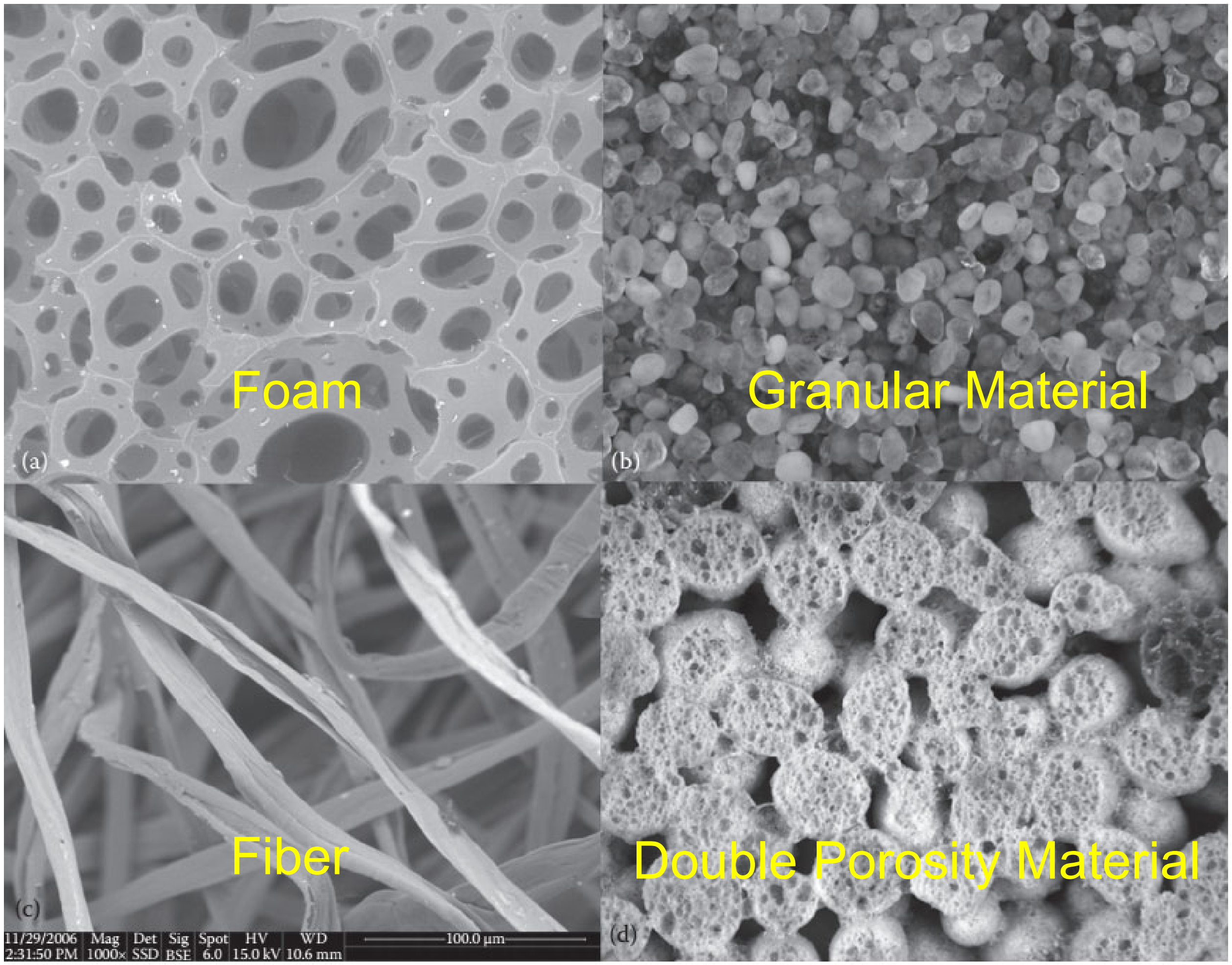
Sound is "absorbed" by converting sound energy to heat within the material, resulting in a reduction of the sound pressure.

Two primary mechanisms:

- vibration of the material skeleton - damping
- friction of the fluid on the skeleton - viscosity

(SEM images courtesy of Jesus Alba, Del Rey Romina, and Vicente Jorge Sanchis, Universitat Politècnica de Valencia and Henkel KGaA. Sand image courtesy of Siim Sepp, commons.wikimedia.org/wiki/File:Sand_from_Gobi_Desert.jpg Licensed under CC BY-SA 3.0.)

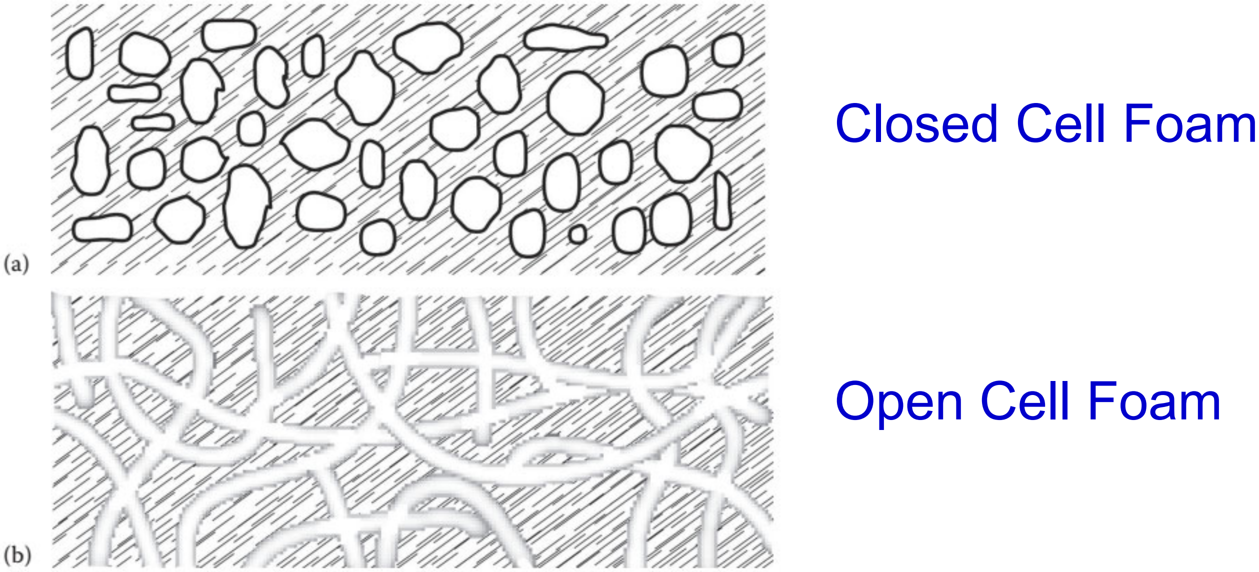
Porous Absorbers Overview



T. J. Cox and P. D'Antonio, 2017

Porous Absorbers Overview

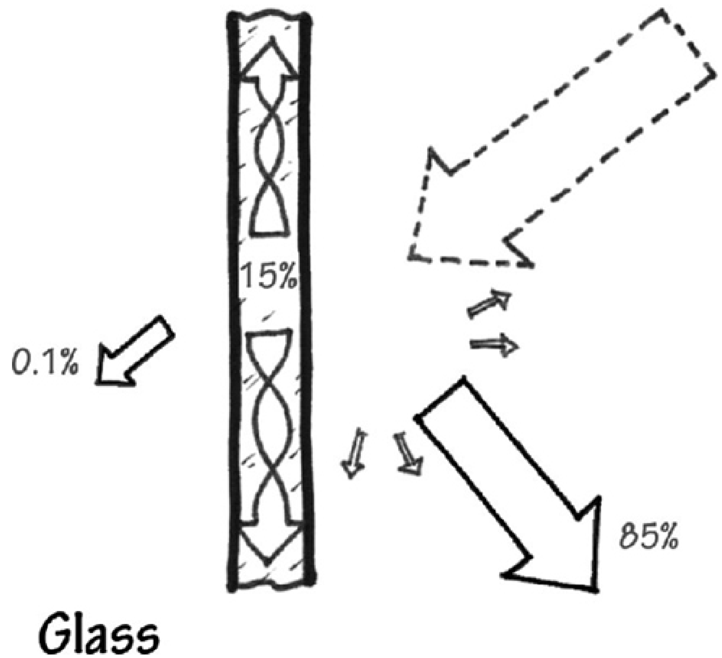
- Foams are made of various materials including polyurethane, polyethylene, and polypropylene.
- Foams are created by a process that has been likened to bread rising.

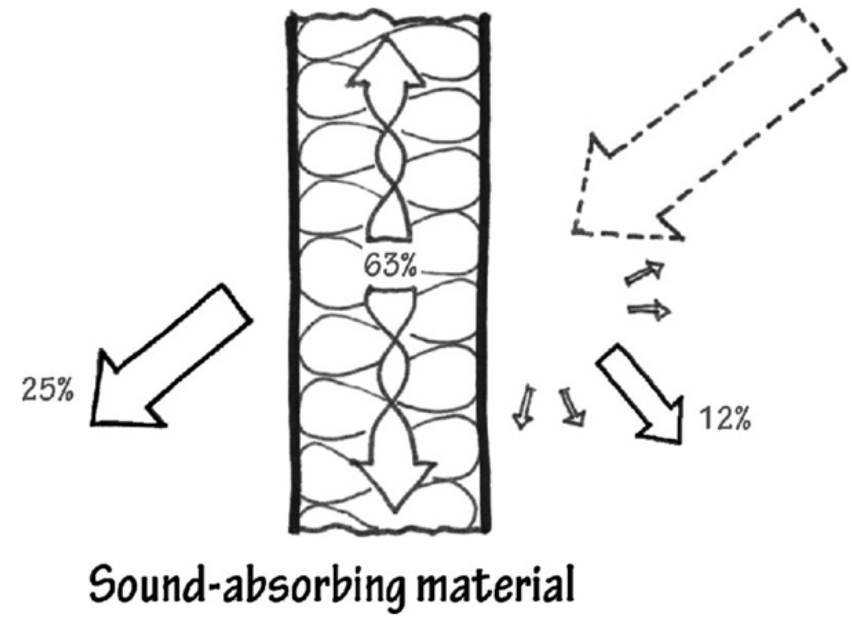


T. J. Cox and P. D'Antonio, 2017 adapted from Cremer and Mueller, 1978

Porous Absorbers Overview

Sound energy is converted to heat via damping or viscosity.





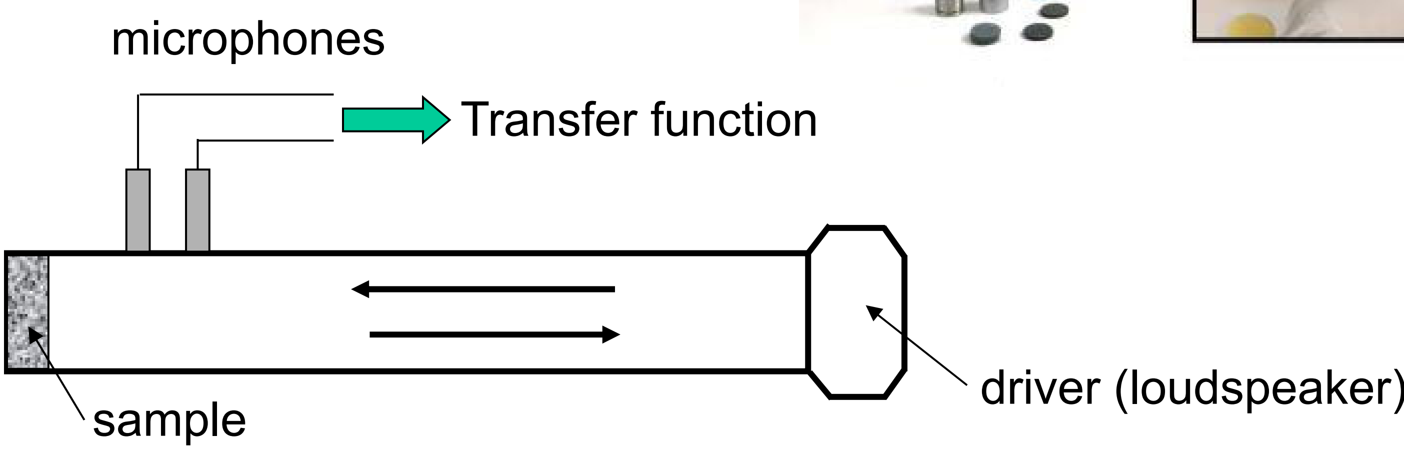
Ermann, 2015

Overview

- Porous Absorbers Overview
- Porous Absorbers Property Determination
- Porous Absorbers Basics for Designers
- Porous Absorbers Compressed
- Porous Absorbers Layered
- Reactive Absorbers Overview
- Reactive Absorbers Example

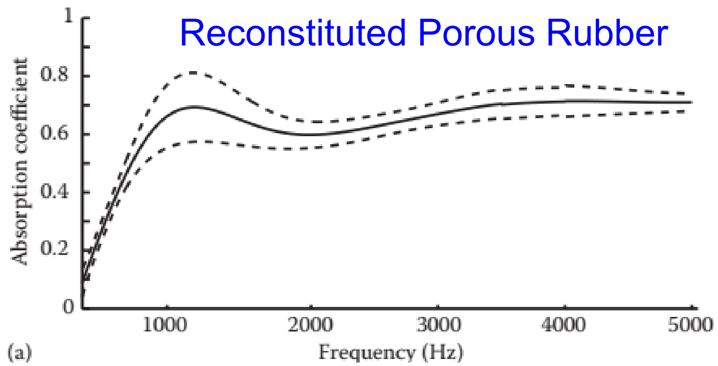
Porous Absorbers Property Determination

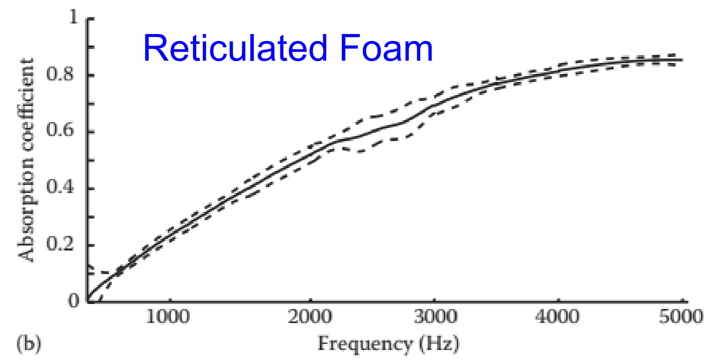
ASTM E1050 – Normal Incident Sound Absorption

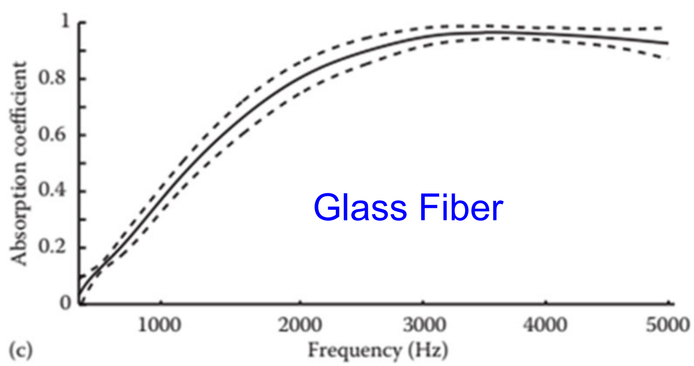


Porous Absorbers Property Determination

ASTM E1050





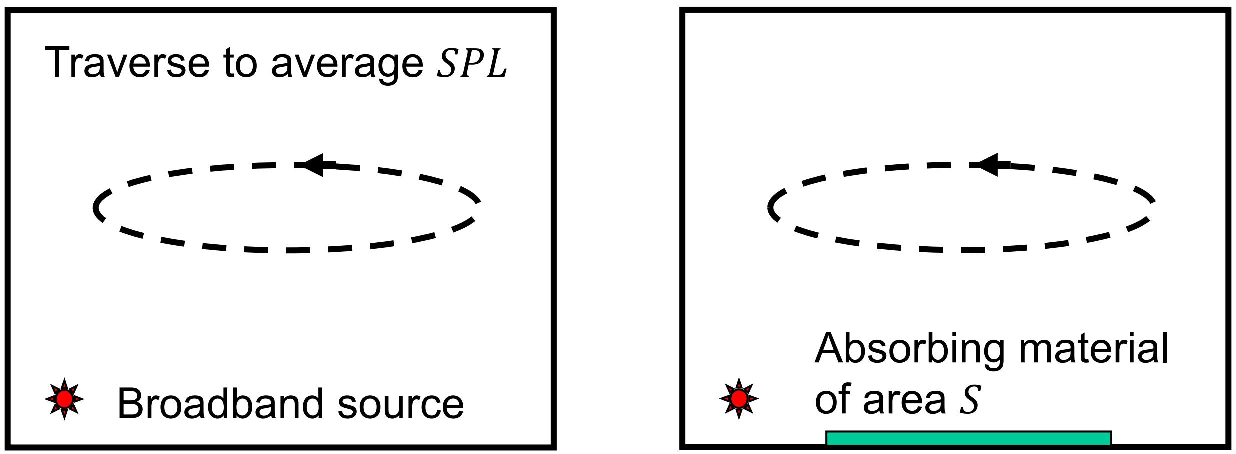


Solid line indicates the mean sound absorption. Error bars indicate the 95% confidence limit in any one laboratory based on round robin tests.

Cox and D'Antonio, 2017 adapted from Horoshenkov et al., 2007

Porous Absorbers Property Determination

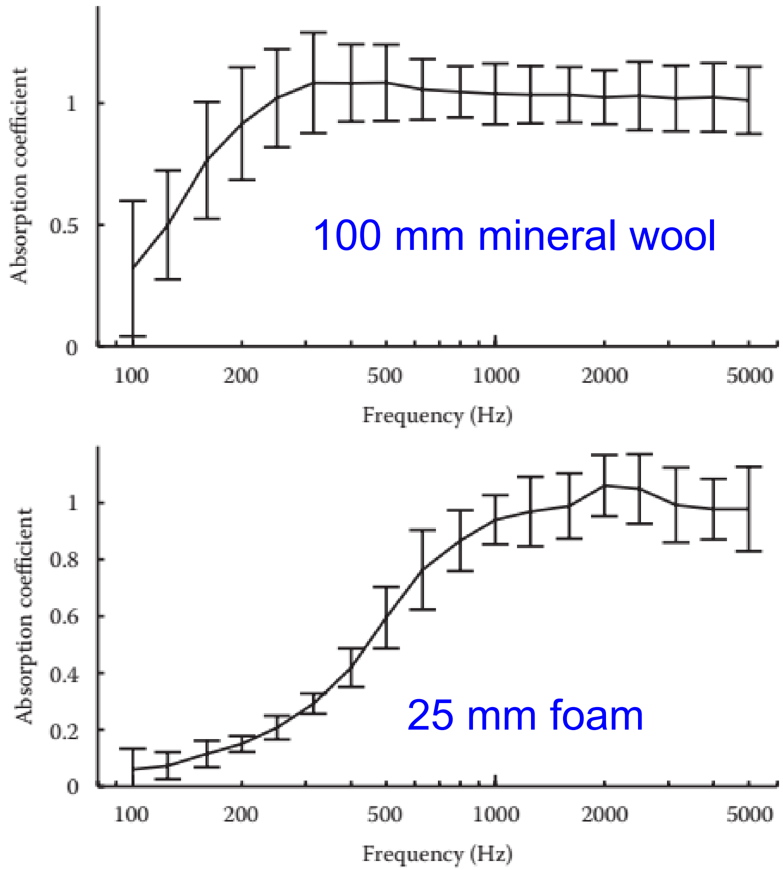
ASTM C423 – Diffuse Field Sound Absorption



Reverberation Room

Porous Absorbers Property Determination

ASTM C423

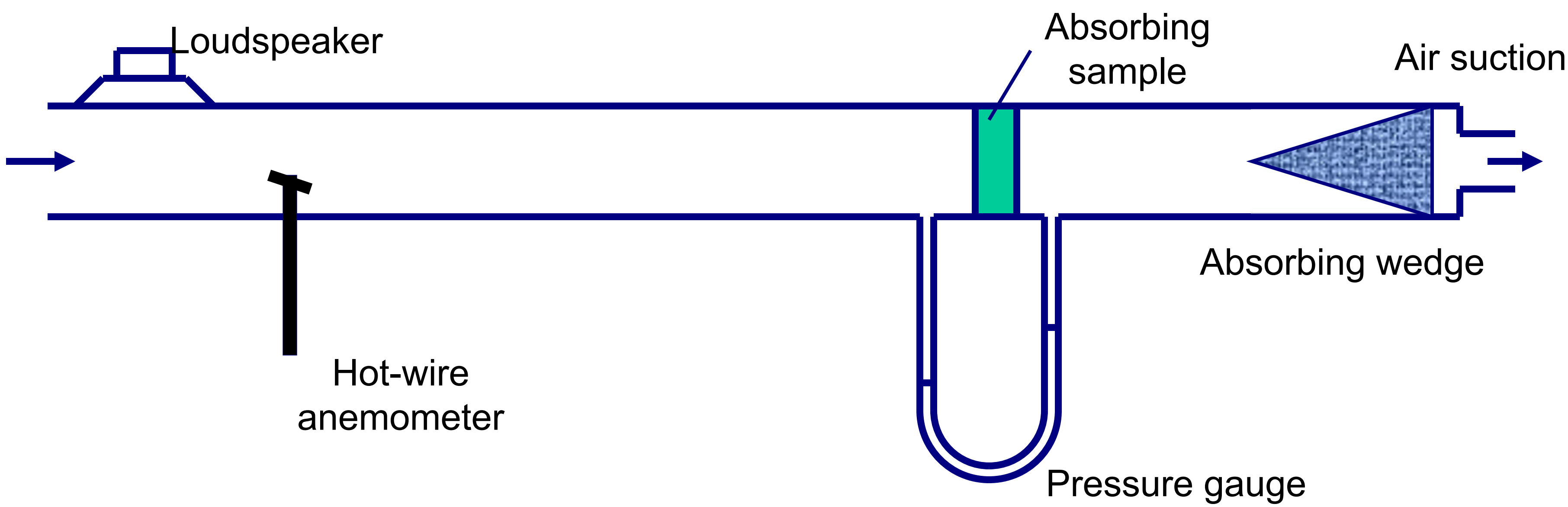


Solid line indicates the mean sound absorption. Error bars indicate the 95% confidence limit in any one laboratory measurement on round robin tests (13 laboratories).

Cox and D'Antonio, 2017 adapted from Horoshenkov et al., 2007

Porous Absorbers Property Determination

Wright-Patterson AFB Study



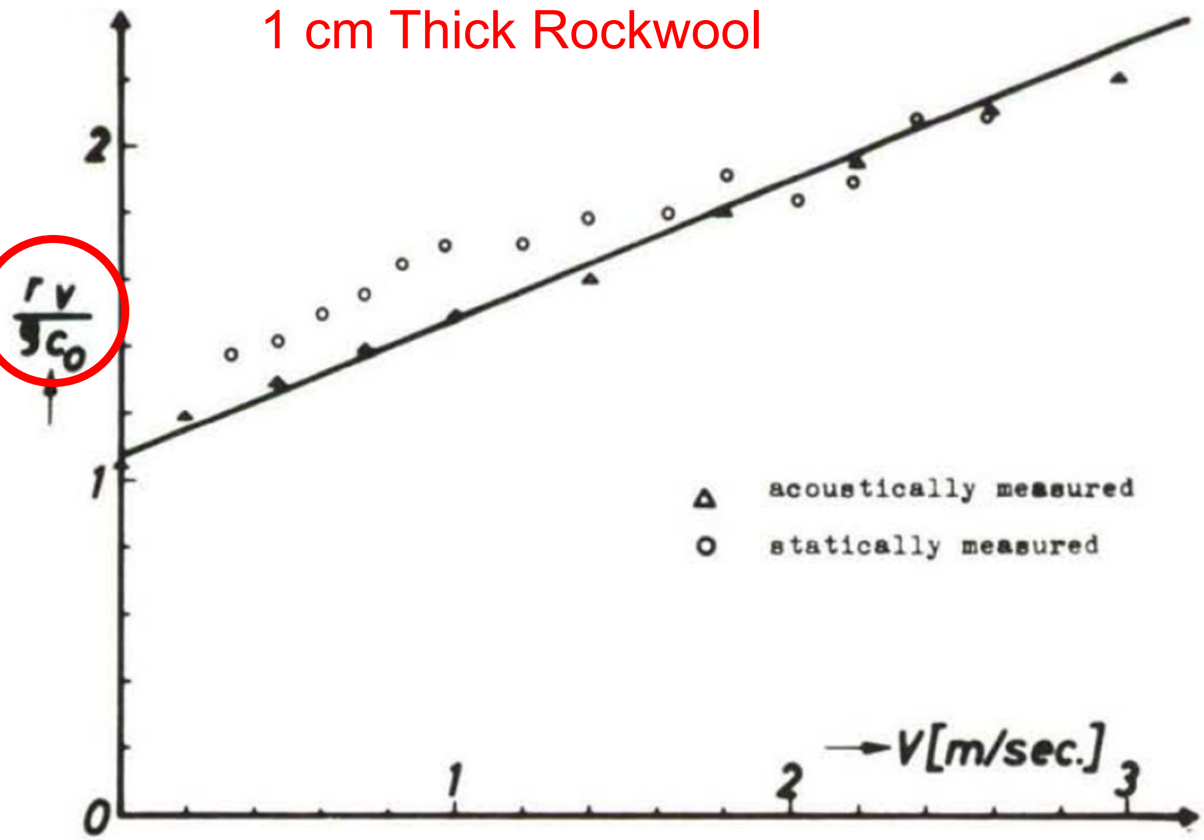
Classic study where both the static and acoustic impedance were measured.

Mechel, Mertens and Schilz (1965)

Porous Absorbers Property Determination

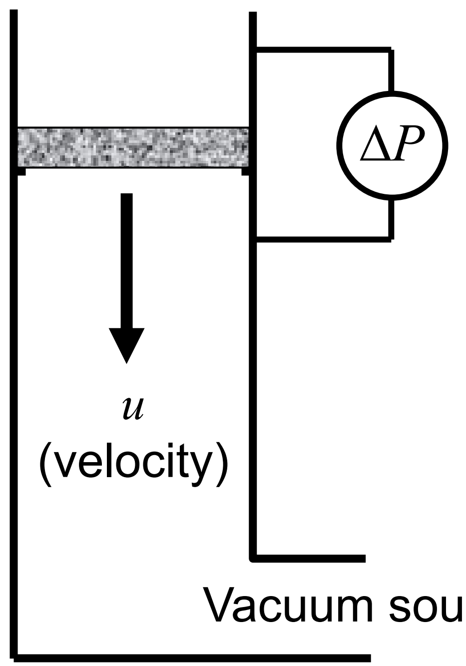
1 cm Thick Rockwool

Acoustic Resistance



Porous Absorbers Property Determination

Standardized in ASTM C522



Flow resistance:

$$r_s = \frac{\Delta P}{u}$$

Flow resistivity:

$$\sigma = \frac{r_s}{t}$$

Porous Absorbers Property Determination

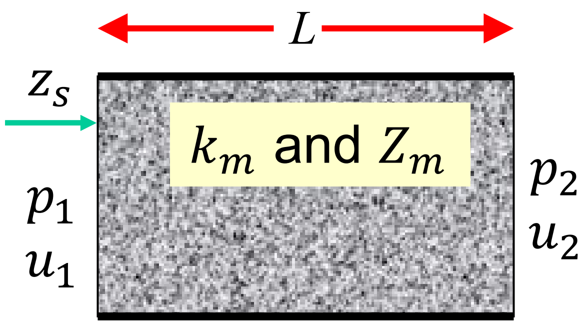
Characteristic Impedance $Z_m = \rho c(1 + C_1 X^{-C_2} - jC_3 X^{-C_4})$

Complex Wavenumber $k_m = \frac{\omega}{c}(1 + C_5 X^{-C_6} - jC_7 X^{-C_8})$

$$\boxed{X = \frac{\rho f}{\sigma}}$$

Material Type Reference	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
Rockwool/fiberglass Delaney and Bazley (1970)	0.0571	0.754	0.087	0.732	0.0978	0.700	0.189	0.595
Rockwool/fiberglass Miki (1989)	0.070	0.632	0.107	0.632	0.109	0.618	0.160	0.618
Polyester Garai and Pompoli (2005)	0.078	0.623	0.074	0.660	0.159	0.571	0.121	0.530
Polyurethane foam of low flow resistivity Dunn and Davern (1986)	0.114	0.369	0.0985	0.758	0.168	0.715	0.136	0.491
Porous plastic foams of medium flow resistivity Wu (1988)	0.209	0.548	0.105	0.607	0.188	0.554	0.163	0.592
Fiber Mechel (2002)								
$X > 0.025$	0.081	0.699	0.191	0.556	0.136	0.641	0.322	0.502
$X < 0.025$	0.0563	0.725	0.127	0.655	0.103	0.716	0.179	0.663

Porous Absorbers Property Determination



$$k_m = \frac{\omega}{c'} \qquad Z_m = \rho' c'$$

Determination of Sound Absorption

$$\begin{Bmatrix} p_1 \\ u_1 \end{Bmatrix} = \begin{bmatrix} \cos(k_m L) & jZ_m \sin(k_m L) \\ j/Z_m \sin(k_m L) & \cos(k_m L) \end{bmatrix} \begin{Bmatrix} p_2 \\ u_2 \end{Bmatrix}$$

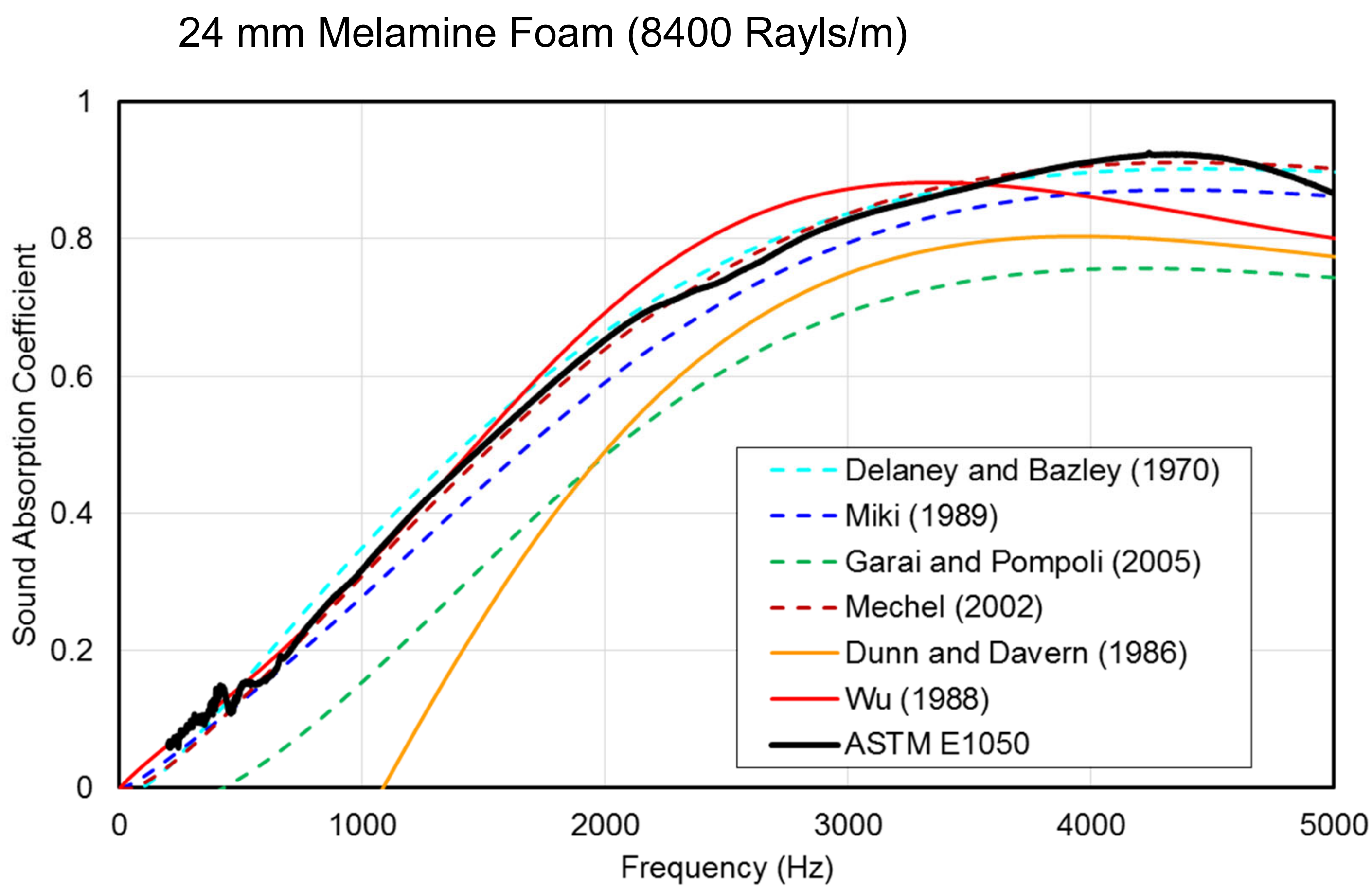
$$\rightarrow z_s = \frac{p_1}{u_1} = -jZ_m \cot(k_m L)$$

$$R = \frac{z_s - \rho c}{z_s + \rho c}$$

$$\rightarrow \alpha = 1 - |R|^2$$

Porous Absorbers Property Determination

Empirical Model Comparison



Porous Absorbers Property Determination

Sound Absorption
ASTM E1050

↓

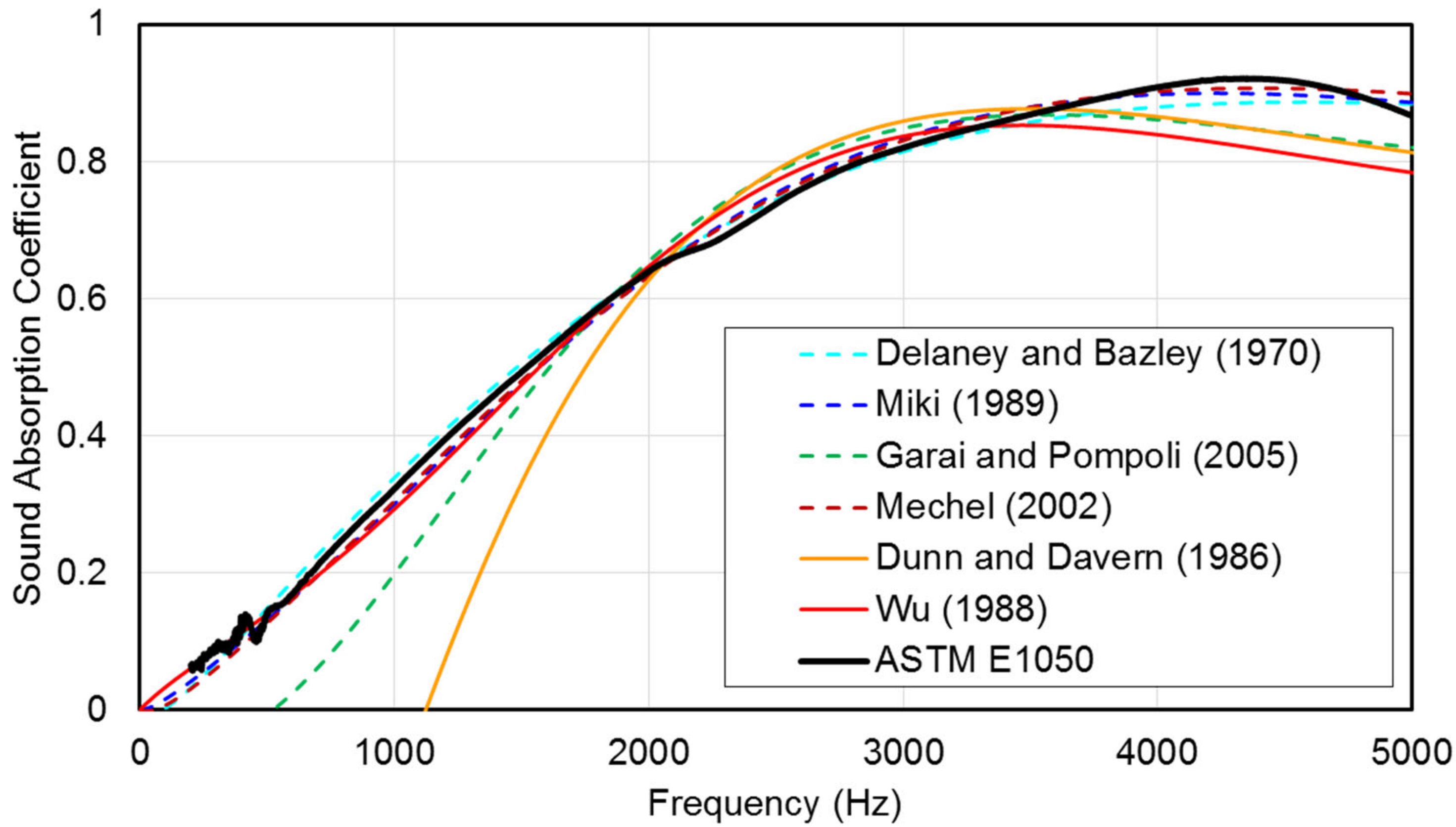
Flow Resistivity
Least Squares Curve Fit

Based on Simón, Fernandez and Pfretzschner, 2006

Porous Absorbers Property Determination

Curve Fit Comparison

24 mm Melamine (8400 Rayls/m)



Porous Absorbers Property Determination

Champoux-Allard Model

- Flow Resistivity
- Porosity
- Tortuosity
- Viscous Characteristic Length
- Thermal Characteristic Length

Johnson-Champoux-Allard Model

- Flow Resistivity
- Porosity
- Tortuosity
- Viscous Characteristic Length
- Thermal Characteristic Length
- Static Thermal Permeability
- Static Viscous Permeability

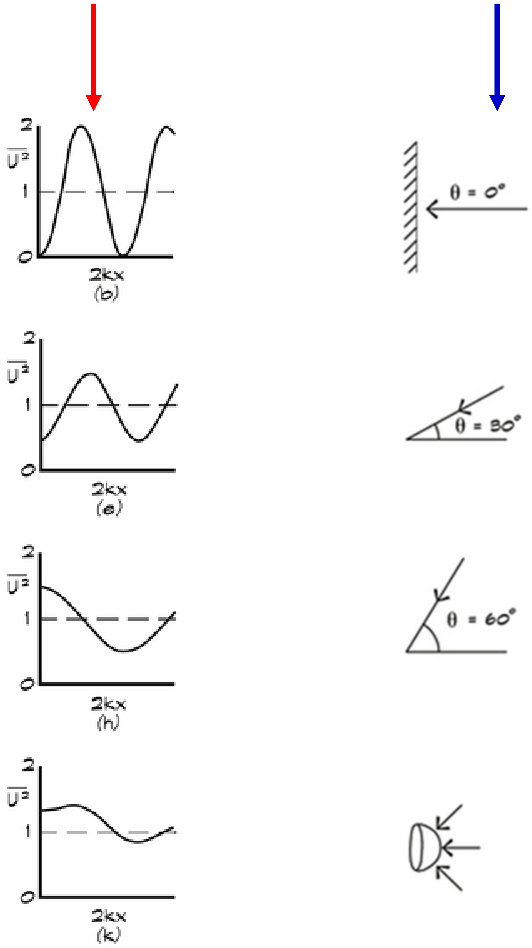
Porous Absorbers Property Determination

Regardless of whether the simple flow resistivity or the more advanced phenomenological models are used, impedance tube measurements are performed, and some material properties are determined via curve fit. Once materials become compressed, which is frequently the case, all bets are off. Hence, we have tended to use the simple flow resistivity models and have had satisfactory results.

Overview

- Porous Absorbers Overview
- Porous Absorbers Property Determination
- <u>Porous Absorbers Basics for Designers</u>
- Porous Absorbers Compressed
- Porous Absorbers Layered
- Reactive Absorbers Overview
- Reactive Absorbers Example

Porous Absorbers Basics for Designers



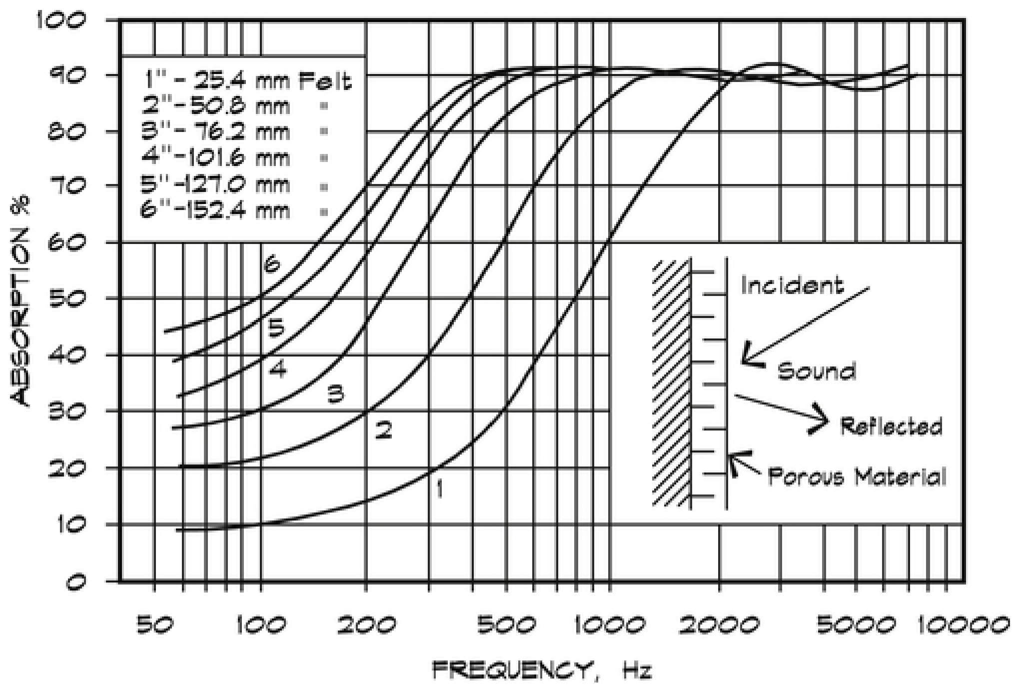
Long, 2014

Takeaways

- Porous sound absorption is less effective at low frequencies because of the long wavelength, small particle velocity, and non-diffuse field.
- Relatively thin sound absorption will have some impact even at lower frequencies if the sound field is diffuse.

Porous Absorbers Basics for Designers

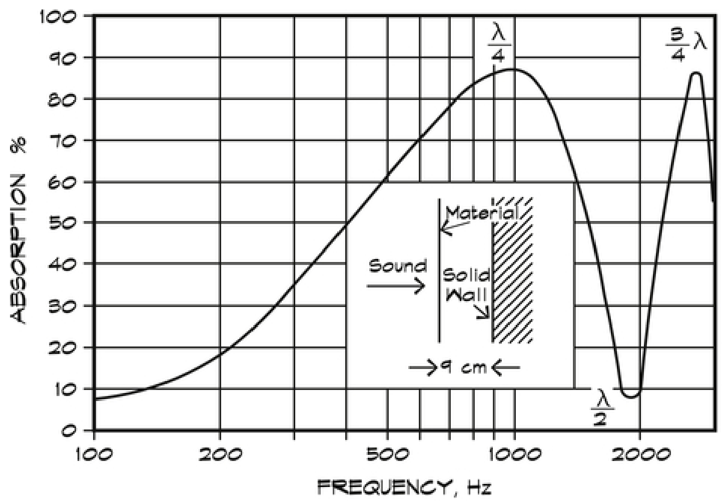
Measured Diffuse Field Sound Absorption



Ginn, 1978 (Reproduced by Long, 2014)

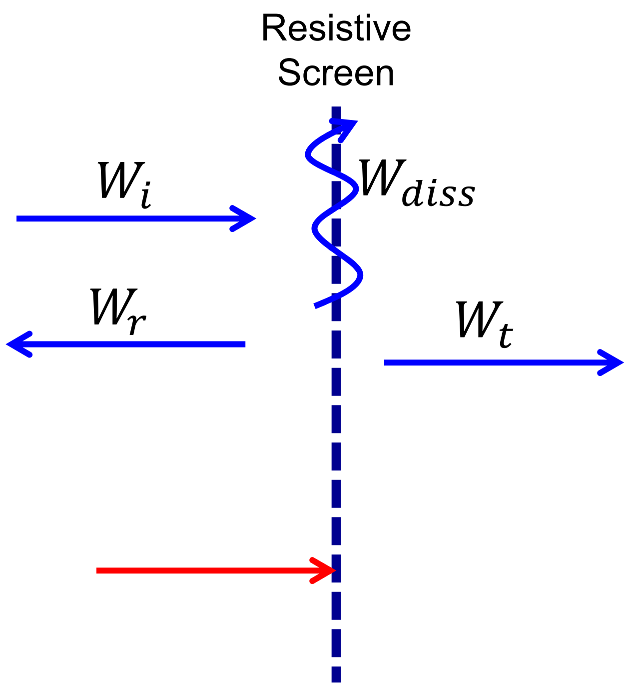
Porous Absorbers Basics for Designers

Thin layer with flow resistance $\sigma_r t$ where σ_r is the flow resistivity and t is the thickness.

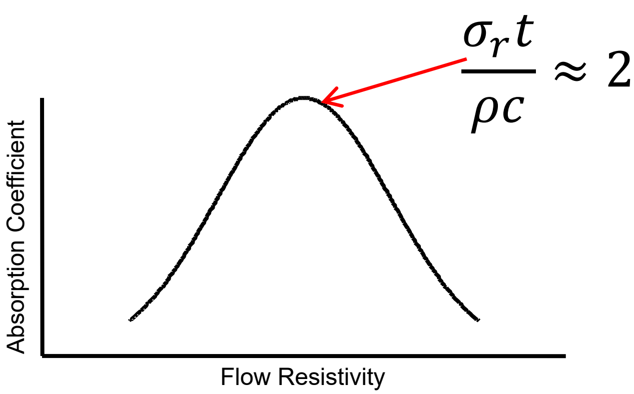


Long, 2014 based on Ginn, 1978

Porous Absorbers Basics for Designers

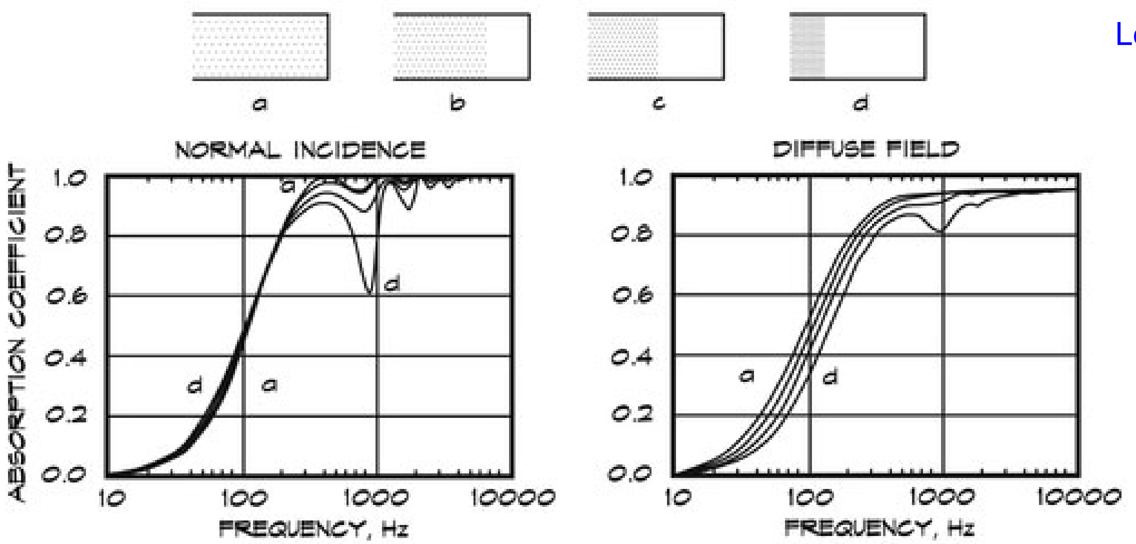


In theory, the dissipated power (W_{diss}) is a maximum when $\sigma_r t = 2\rho c$. A general rule of thumb is that a sound absorber will be effective when $\sigma_r t \approx n\rho c$ where n is on the order of 2. This assumes that the acoustic resistance is equal to the static flow resistance.



Porous Absorbers Basics for Designers

Thin layer with flow resistance $\sigma_r t$ where σ_r is the flow resistivity and t is the thickness.



Long, 2014 based on Ingard, 1994

$\sigma_r t = 2\rho c$ for each case

Overview

- Porous Absorbers Overview
- Porous Absorbers Property Determination
- Porous Absorbers Basics for Designers
- Porous Absorbers Compressed
- Porous Absorbers Layered
- Reactive Absorbers Overview
- Reactive Absorbers Example

Porous Absorbers Compressed

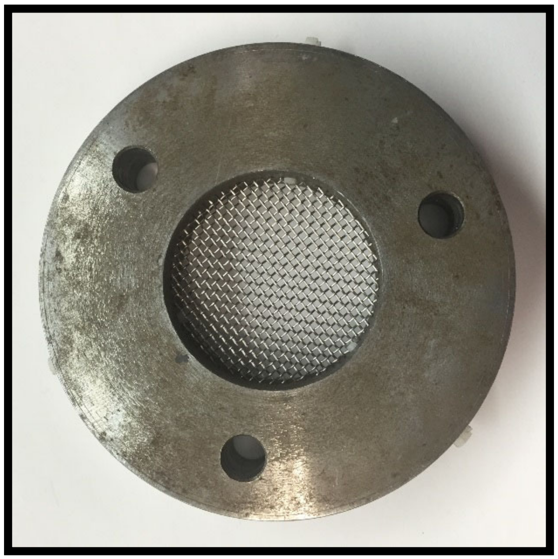
24 mm
Melamine Foam

28.5 mm
Polyurethane Foam

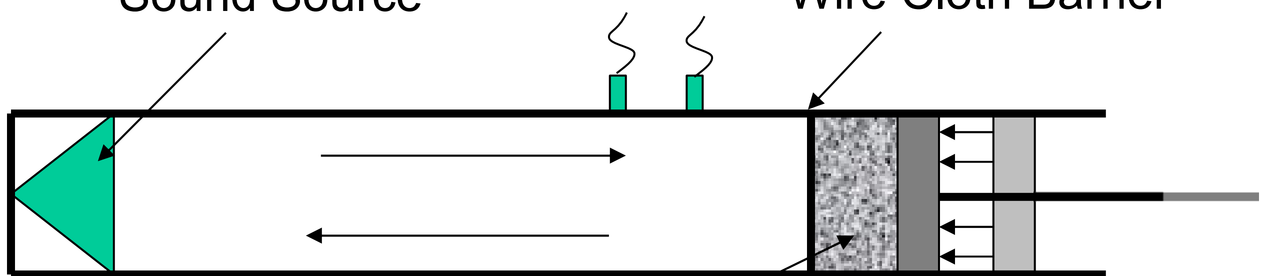
40 mm
Polyester Fiber

50.8 mm
Glass Wool Fiber

Porous Absorbers Compressed

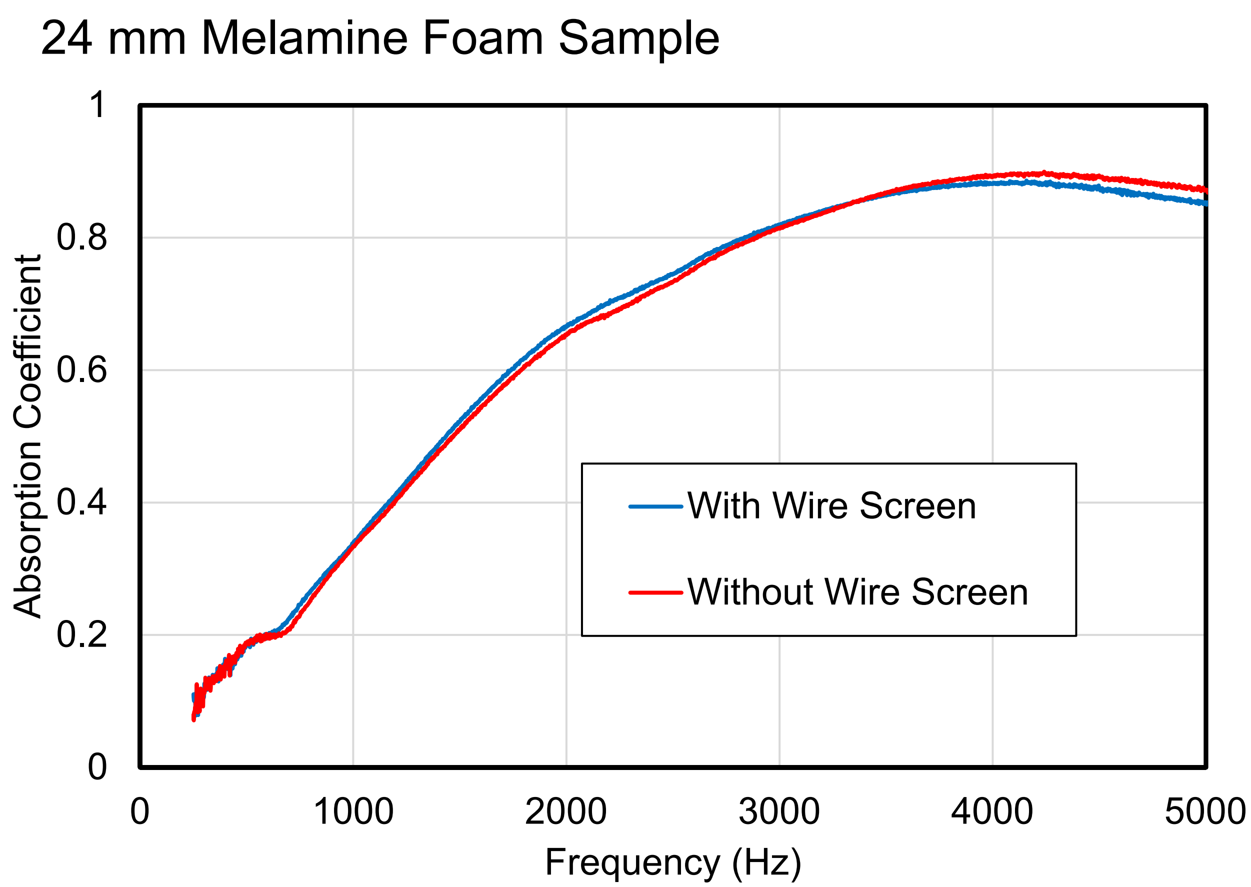


Wire Screen Barrier



Porous Absorbers Compressed

Effect of Wire Screen on Absorption



Porous Absorbers Compressed

Compressed Sound Absorber

↓

Sound Absorption
ASTM E1050

↓

Flow Resistivity
Least Squares Curve Fit

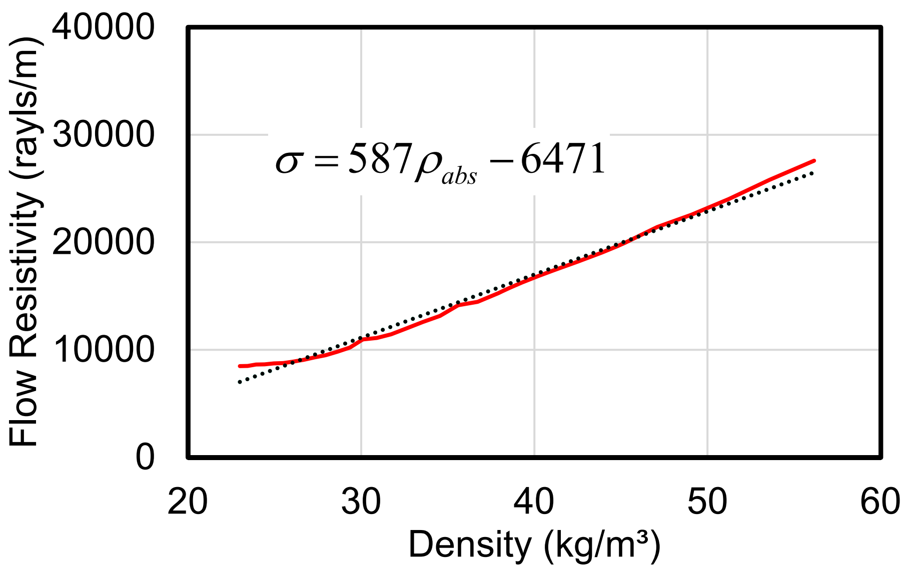
↓

Relationship Between Flow Resistivity and Density

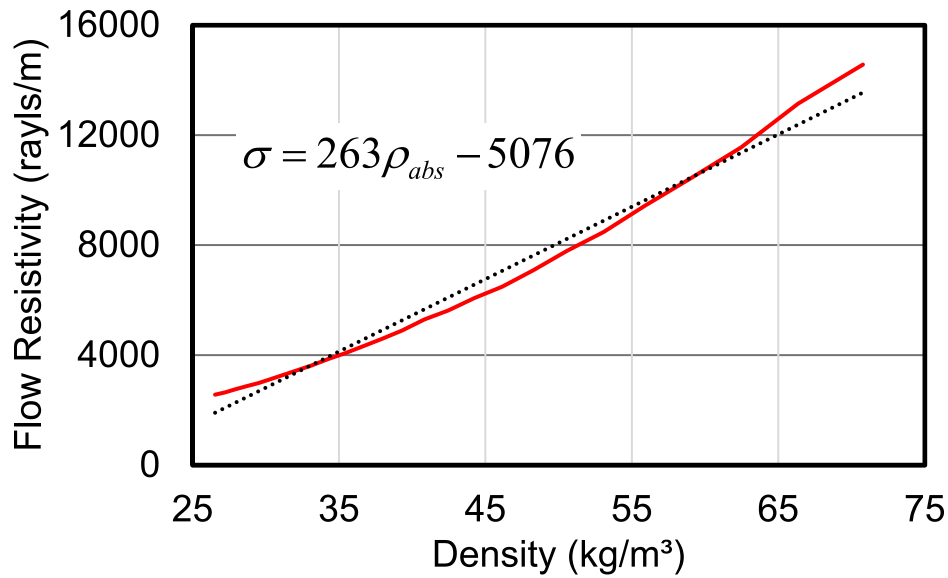
Porous Absorbers Compressed

Flow Resistivity vs. Density

50.8 mm Glass Wool

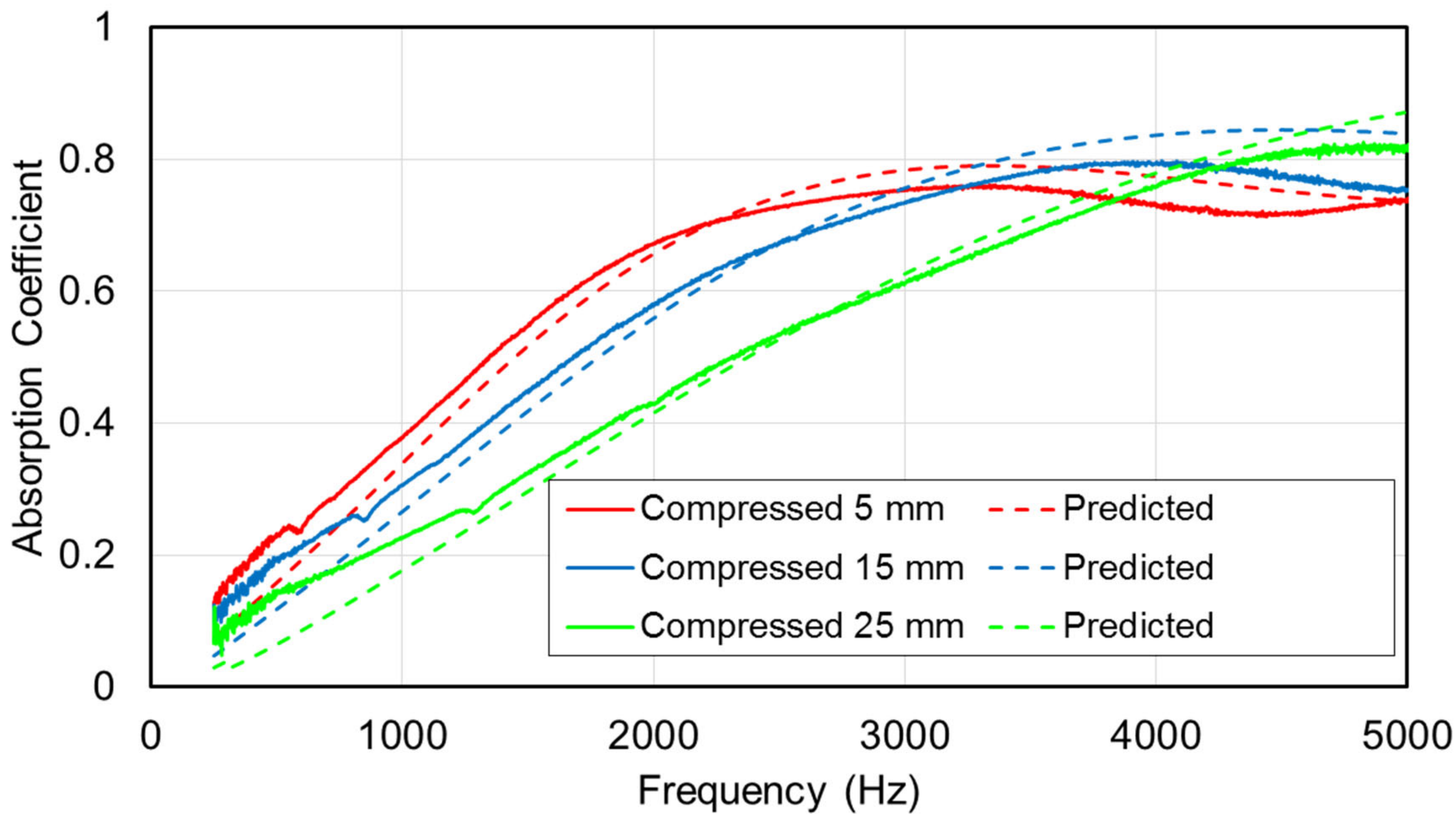


40 mm Polyester Fiber



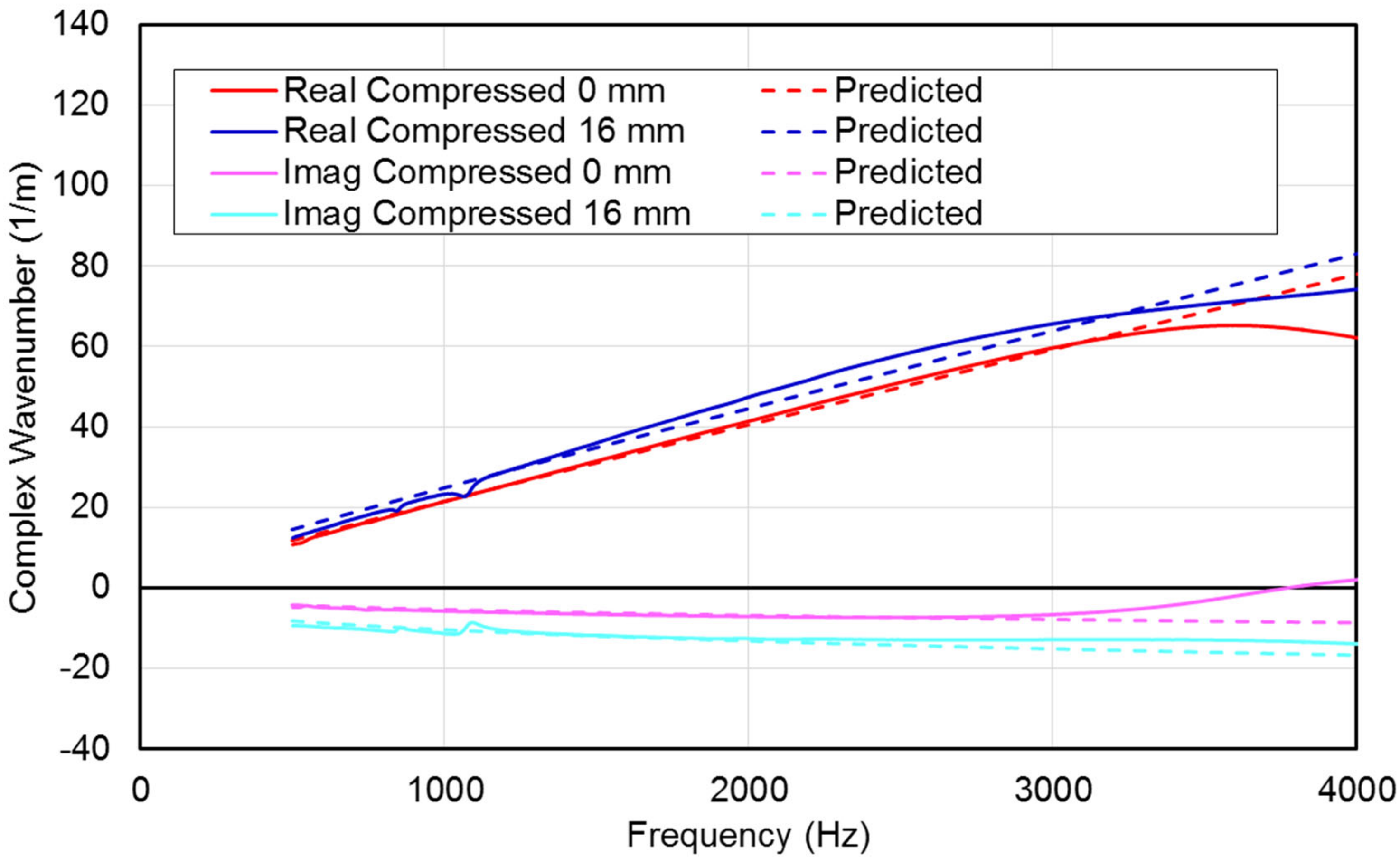
Porous Absorbers Compressed

40 mm Polyester Fiber



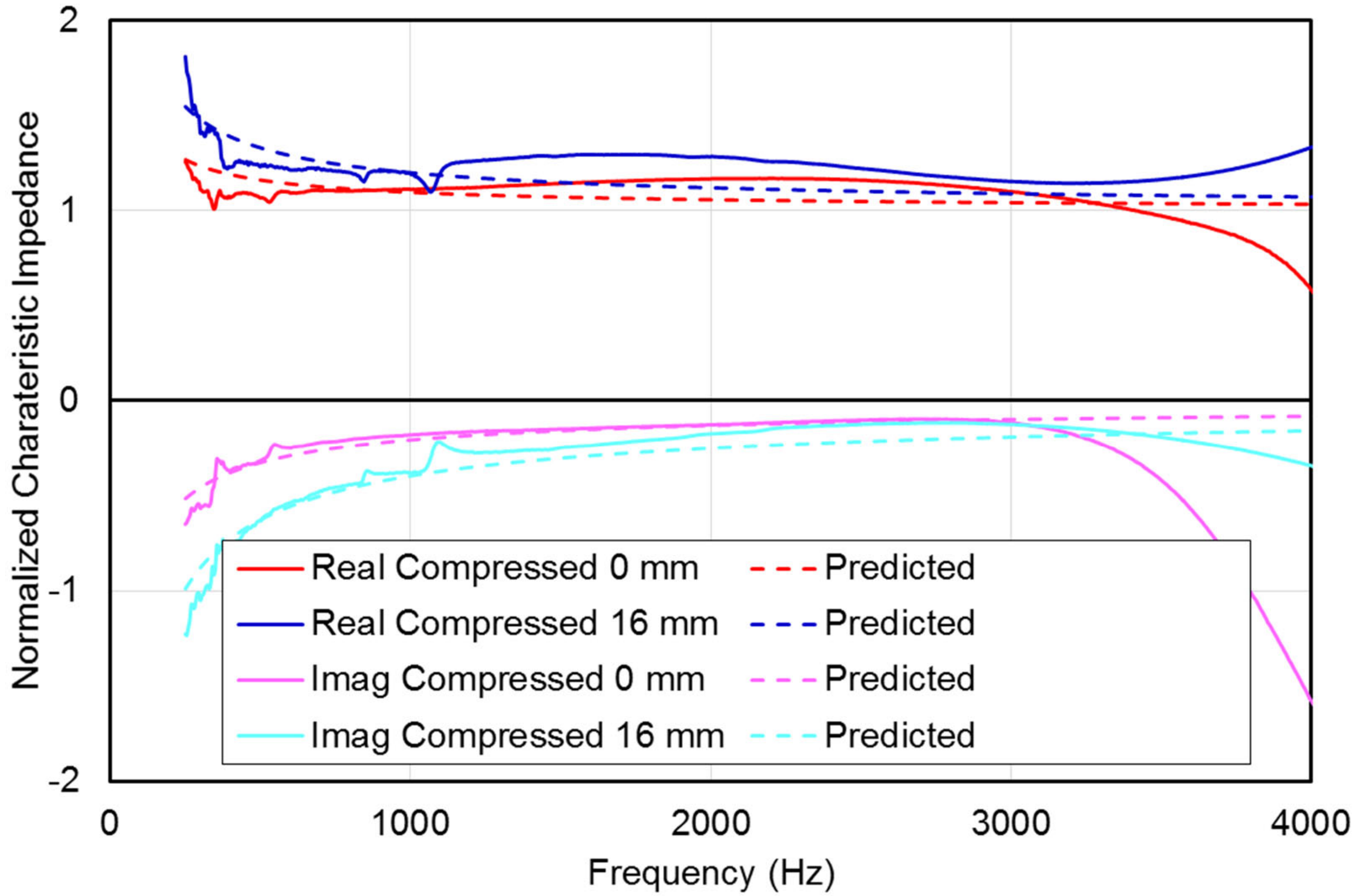
Porous Absorbers Compressed

Complex Wavenumber Polyester Fiber



Porous Absorbers Compressed

Characteristic Impedance Polyester Fiber



Overview

- Porous Absorbers Overview
- Porous Absorbers Property Determination
- Porous Absorbers Basics for Designers
- Porous Absorbers Compressed
- Porous Absorbers Layered
- Reactive Absorbers Overview
- Reactive Absorbers Example

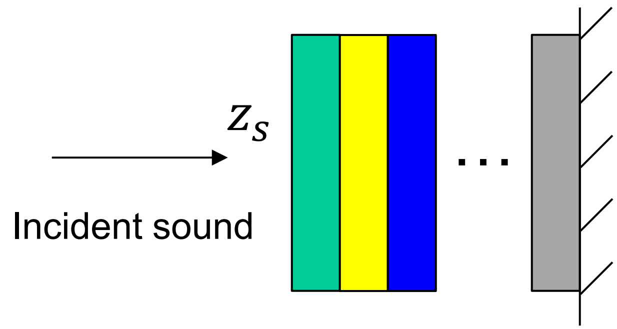
Porous Absorbers Layered

$$[T] = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = [T_1][T_2][T_3]\ldots[T_n]$$

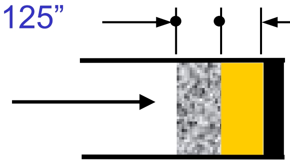
$$\longrightarrow z_s = \frac{T_{11}}{T_{21}}$$

$$R = \frac{z_1 - \rho c}{z_1 + \rho c}$$

$$\longrightarrow \alpha = 1 - |R|^2$$



Porous Absorbers Layered Materials



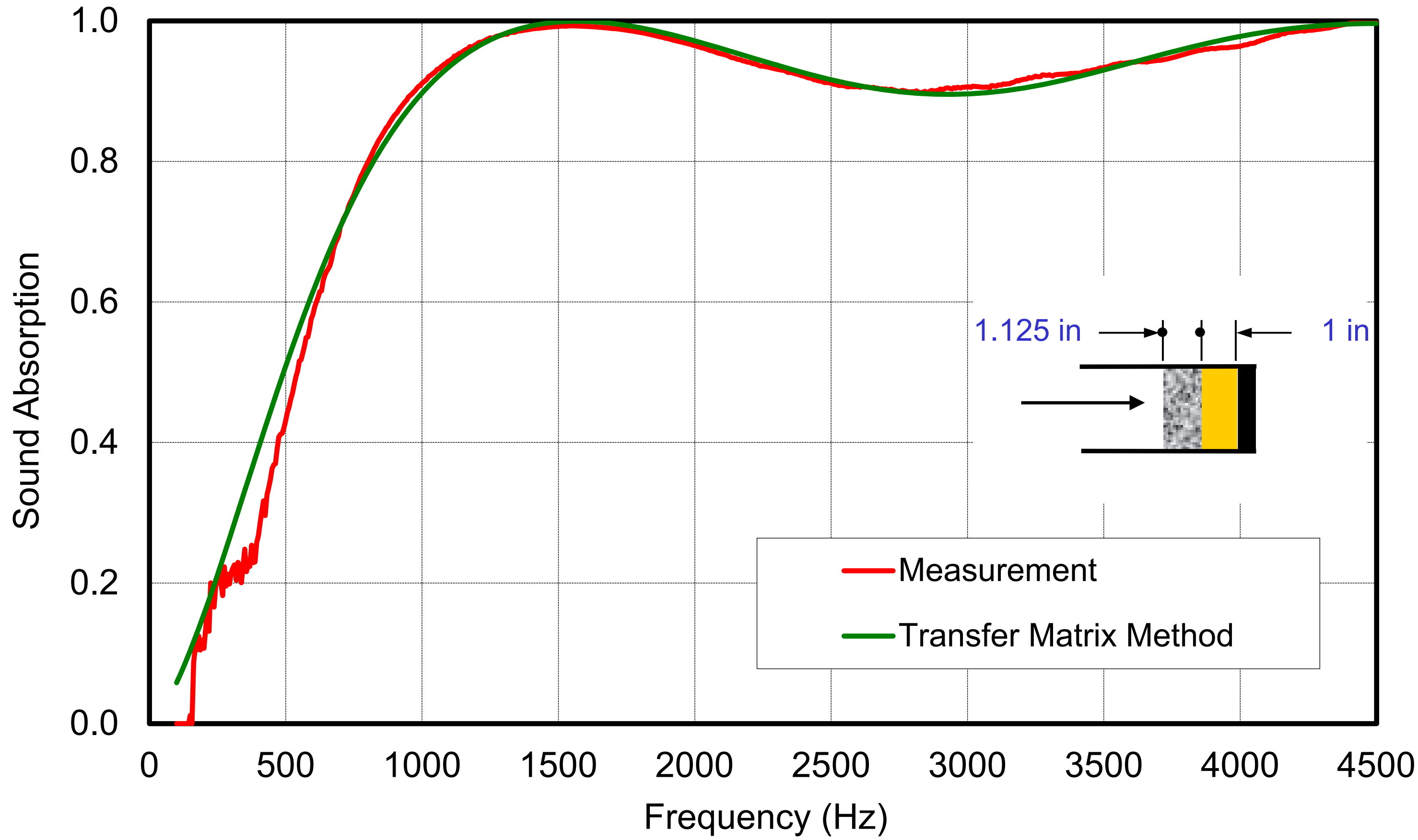
Curve Fit using Fiber Model

1.125 inch Fiber	→	$\sigma = 10312$ rayls/m

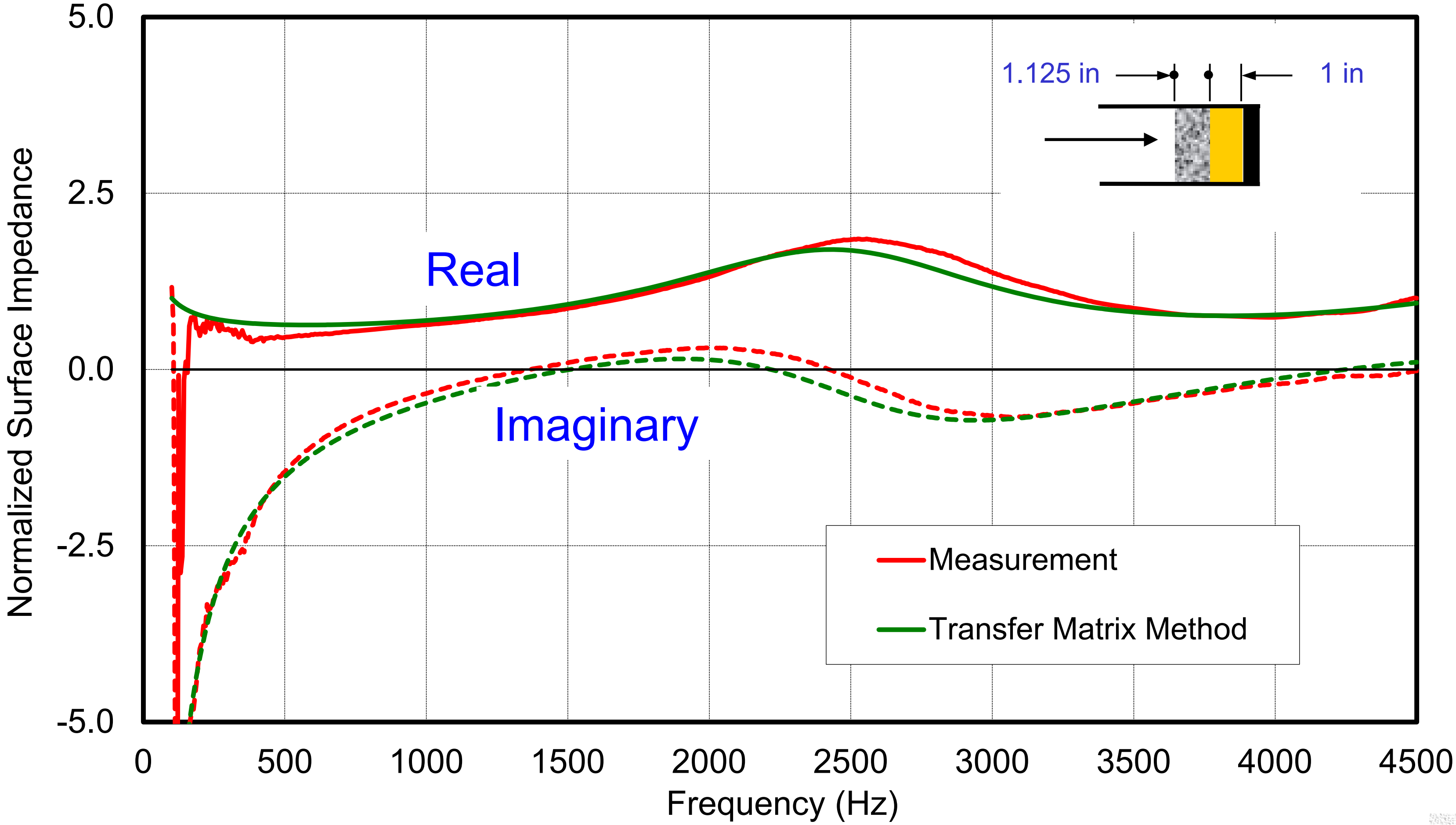
Curve Fit using Foam Model

1 inch Foam	→	$\sigma = 4930$ rayls/m

Porous Absorbers Layered



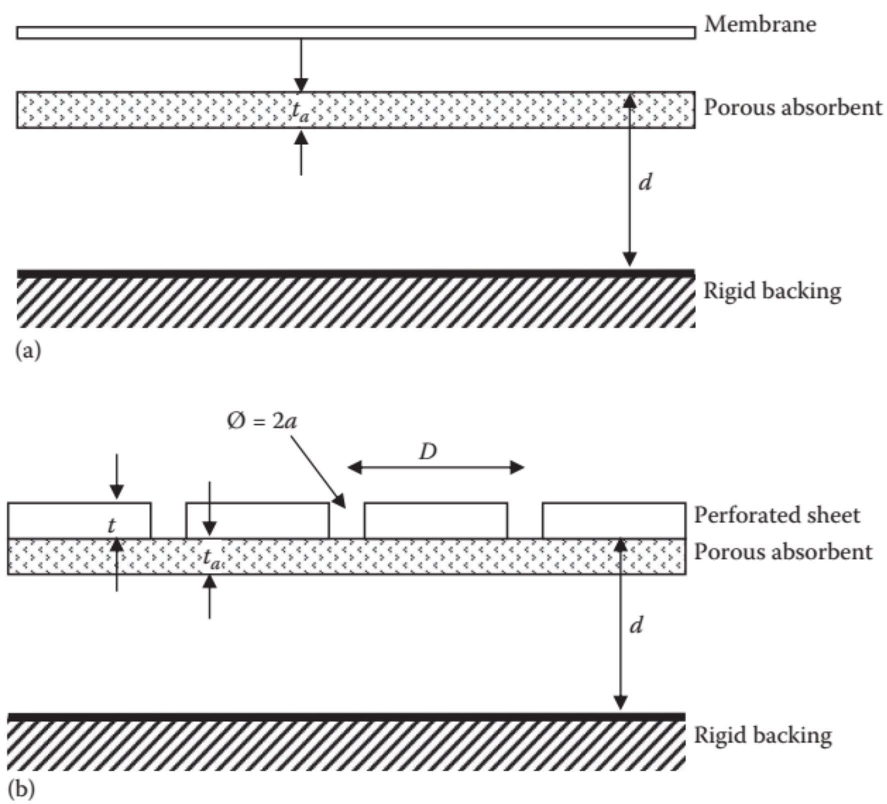
Porous Absorbers Layered

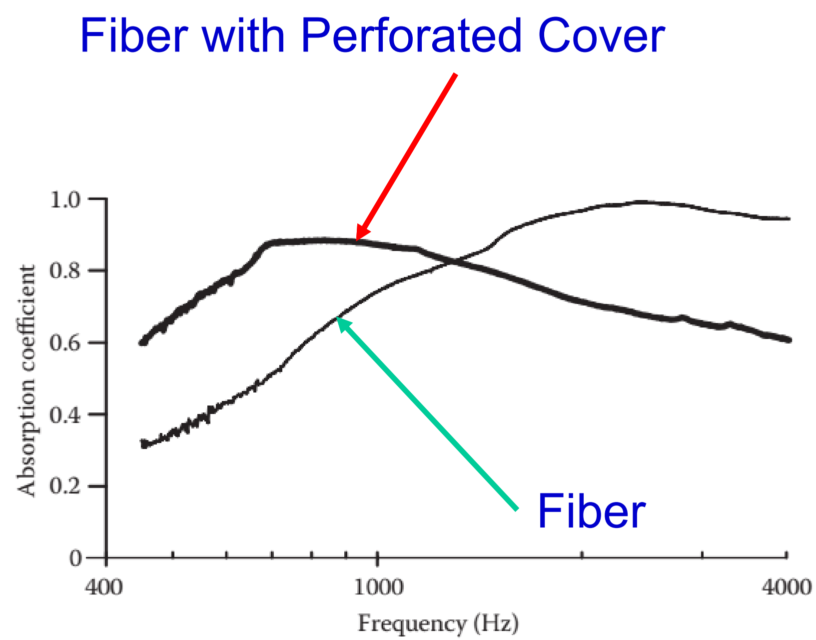


Overview

- Porous Absorbers Overview
- Porous Absorbers Property Determination
- Porous Absorbers Basics for Designers
- Porous Absorbers Compressed
- Porous Absorbers Layered
- Reactive Absorbers Overview
- Reactive Absorbers Example

Reactive Absorbers Overview



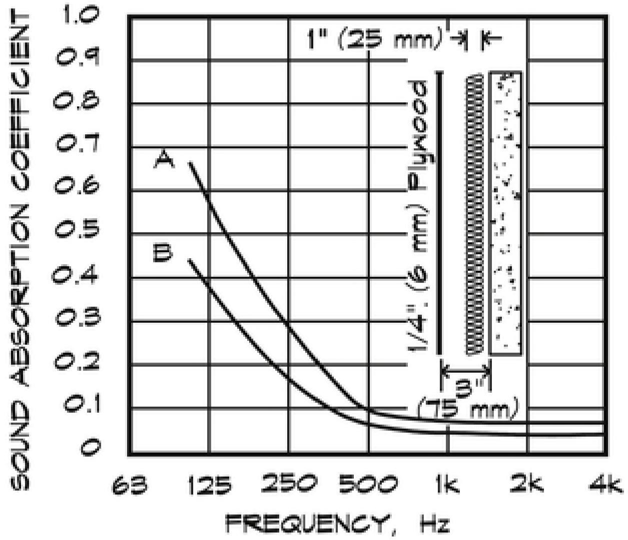


Reactive Absorbers Overview

$$f_r = \frac{1}{2\pi}\sqrt{\frac{\rho c^2}{m_s d}}$$

m_s surface mass density
d spacing from wall

A – with 1 in glass fiber
B – no glass fiber



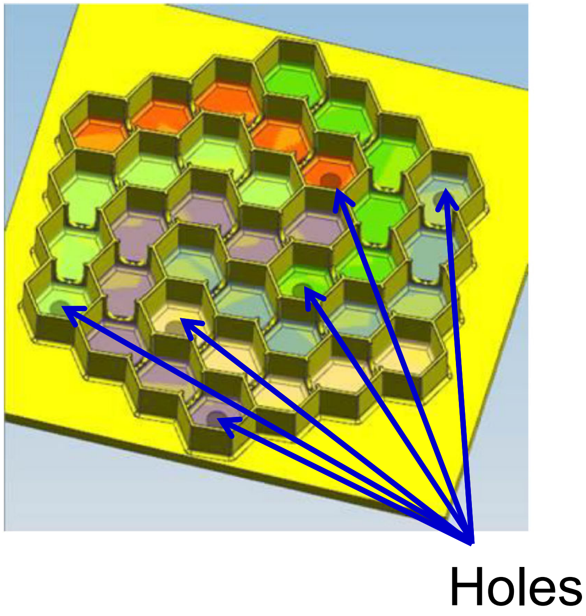
Long, 2014 based on Doelle, 1972

Overview

- Porous Absorbers Overview
- Porous Absorbers Property Determination
- Porous Absorbers Basics for Designers
- Porous Absorbers Compressed
- Porous Absorbers Layered
- Reactive Absorbers Overview
- Reactive Absorbers Example

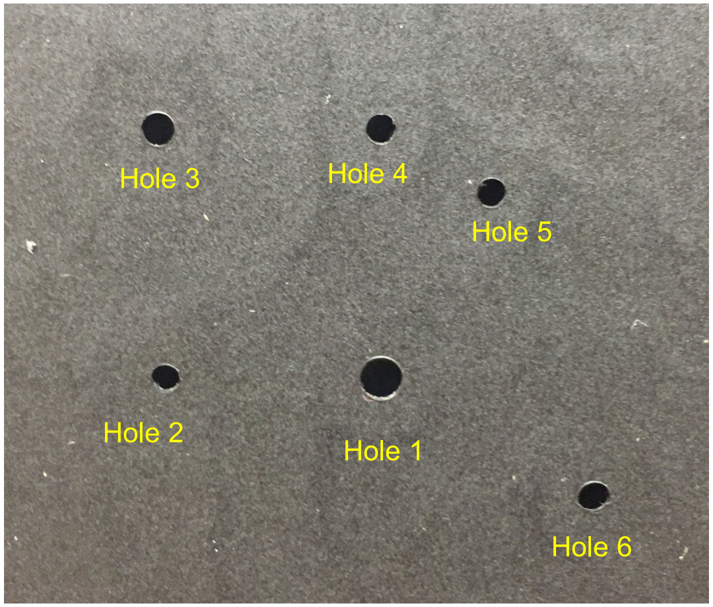
Reactive Absorbers Example

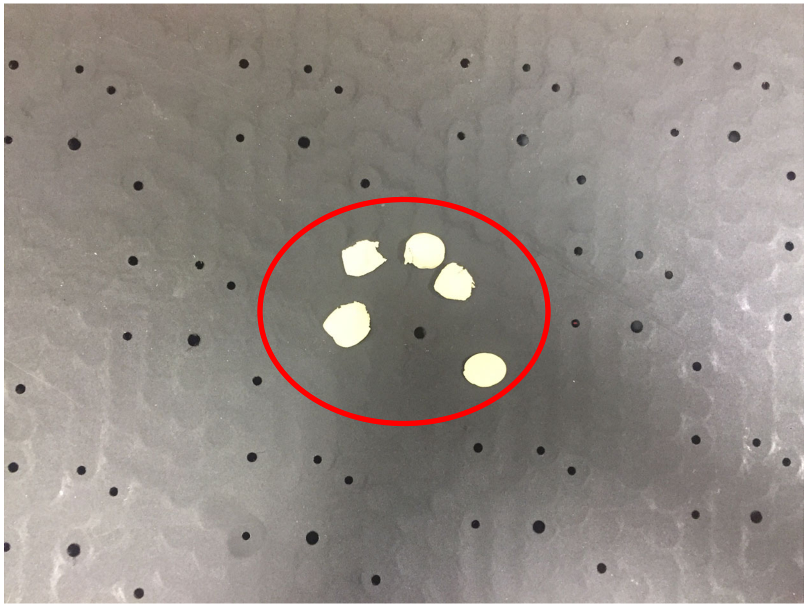
Honeycomb with interconnected cells.



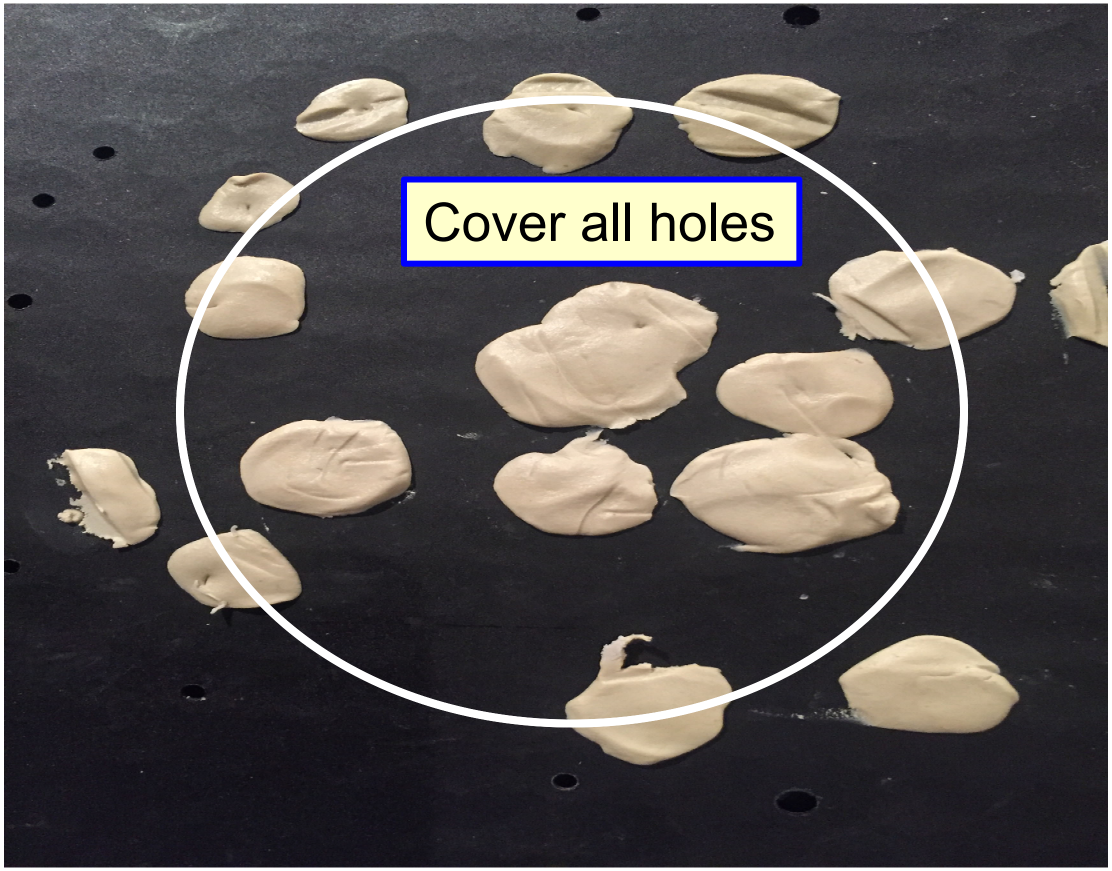
Jonza, J., Herdtle, T., Kalish, J., Gerdes, R., and Eichhorn, G., Acoustically Absorbing Lightweight Thermoplastic Honeycomb Panels, SAE International Journal of Vehicle Dynamics, Stability, and NVH 1(2):2017, doi:10.4271/2017-01-1813.

Reactive Absorbers Example

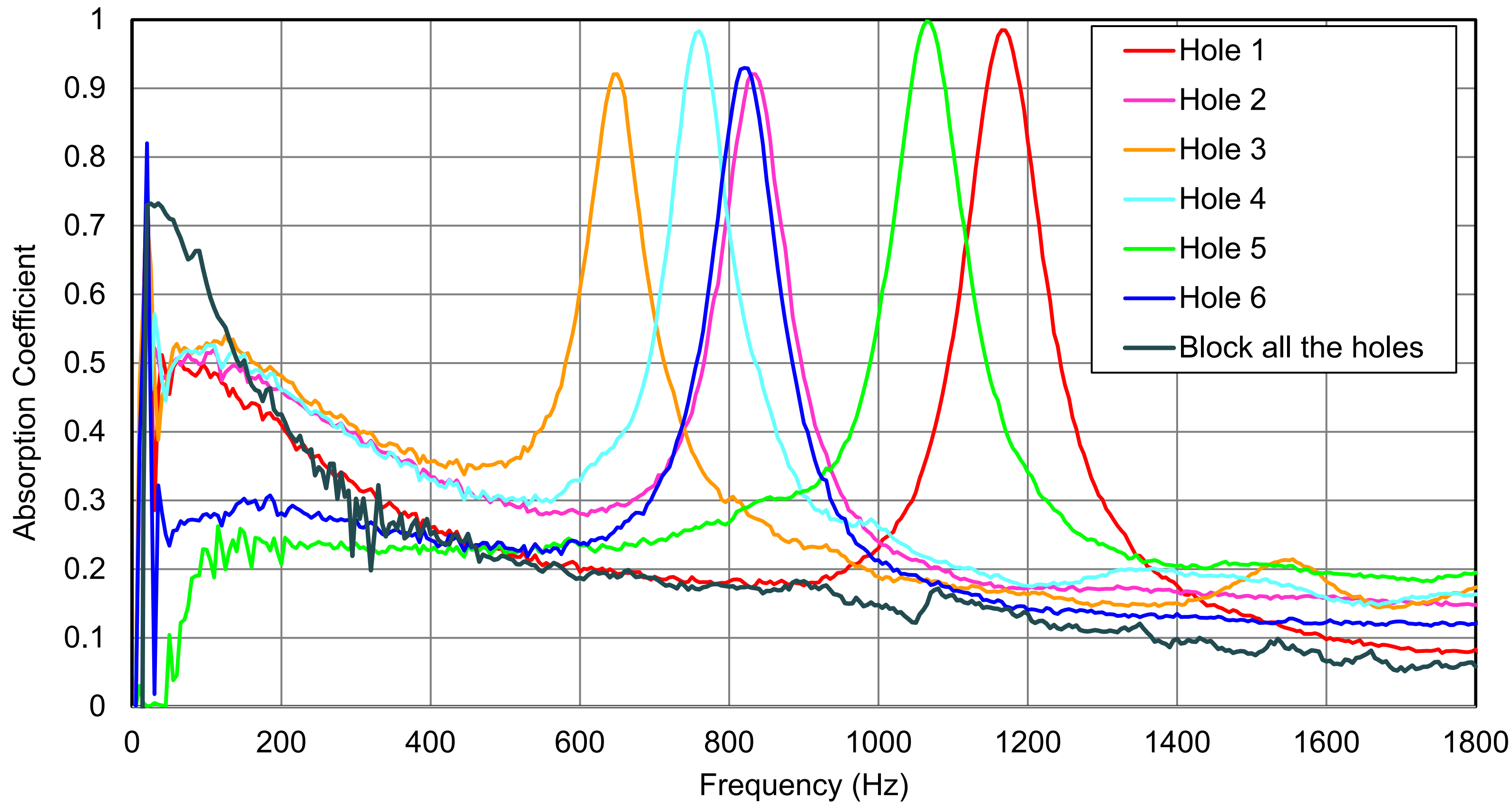




Reactive Absorbers Example

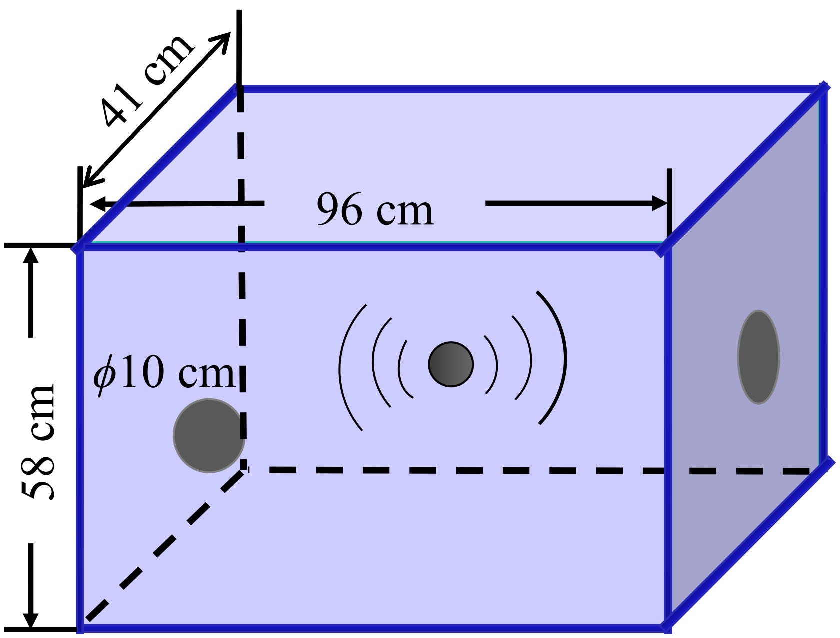


Reactive Absorbers Example



Reactive Absorbers Example

Baseline Case

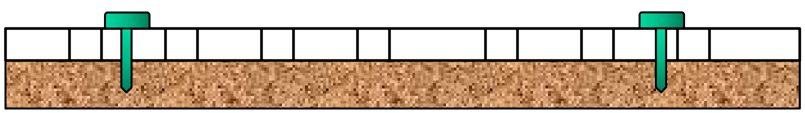


Reactive Absorbers Example

1.5 in Fiber Treatment

Reactive Absorbers Example

Enclosure Study



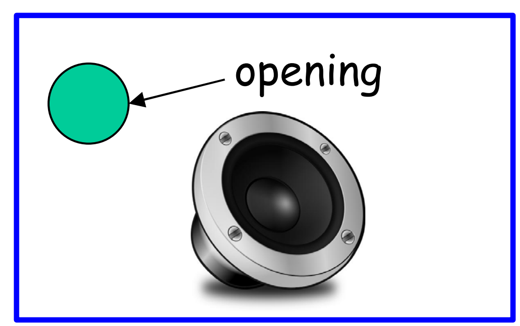
Reactive Absorbers Example

$$IL = SWL_0 - SWL_1$$

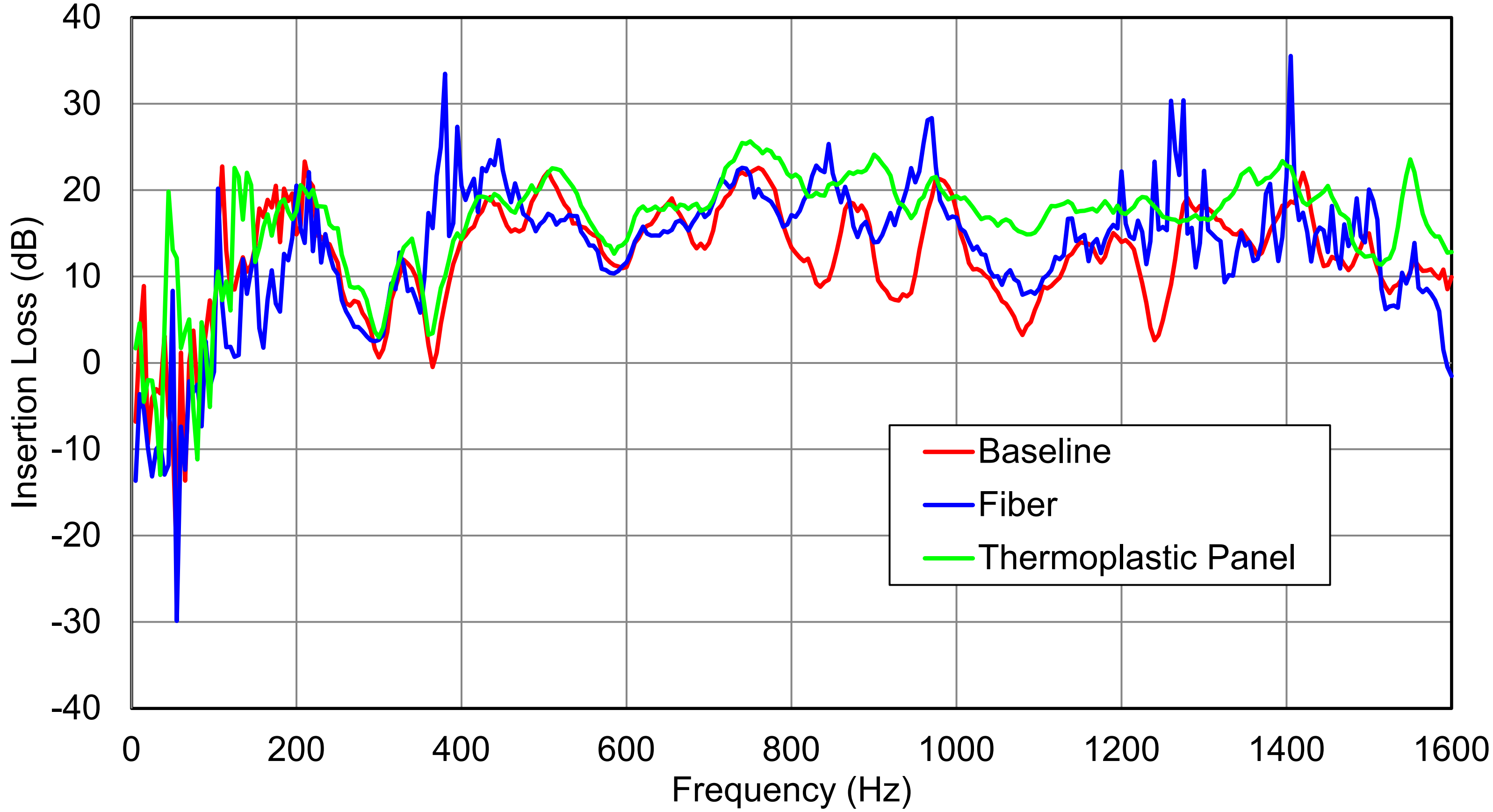
SWL_0 is the sound power level in dB for the speaker
SWL_1 is the dB level with the enclosure covered.

SWL_0

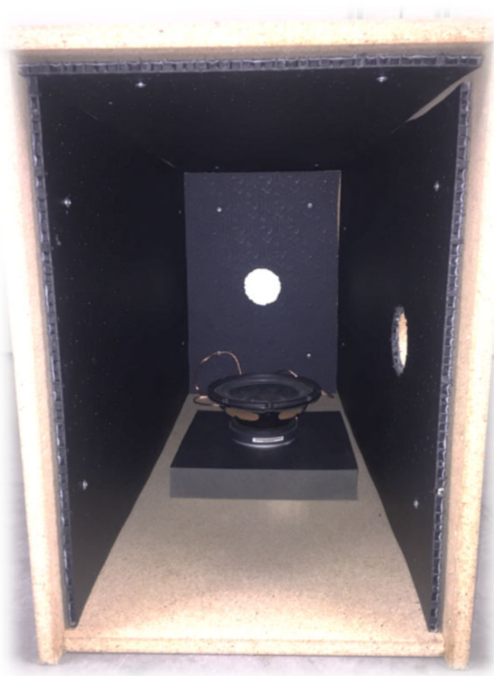
SWL_1



Reactive Absorbers Example

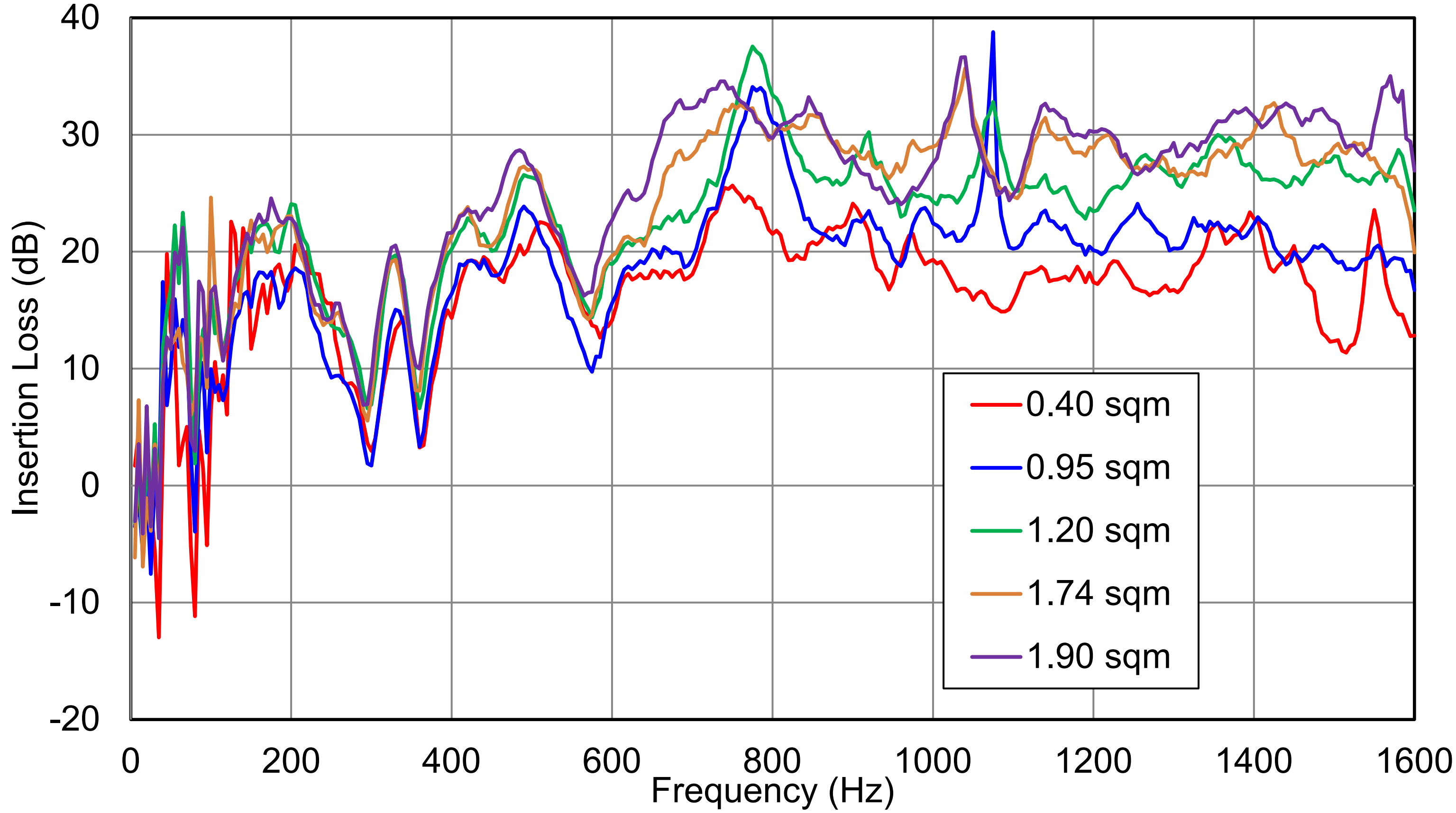


Reactive Absorbers Example



Reactive Absorbers Example

Effect of Panel Area

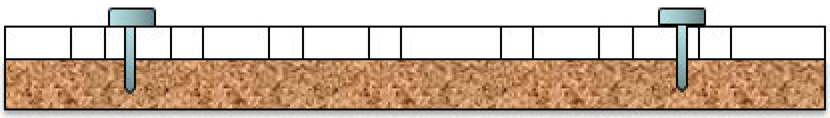


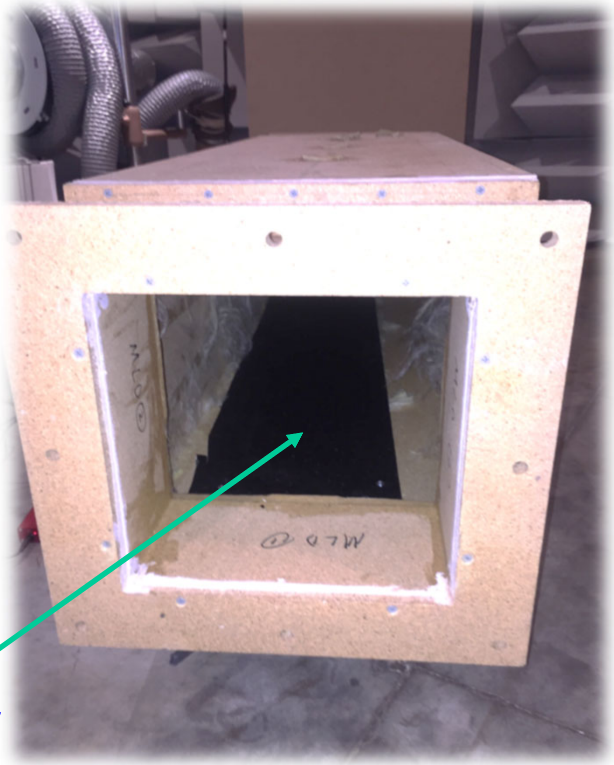
Reactive Absorbers Example

Reference Measurement

$$IL = L_{W,reference} - L_{W,silencer}$$

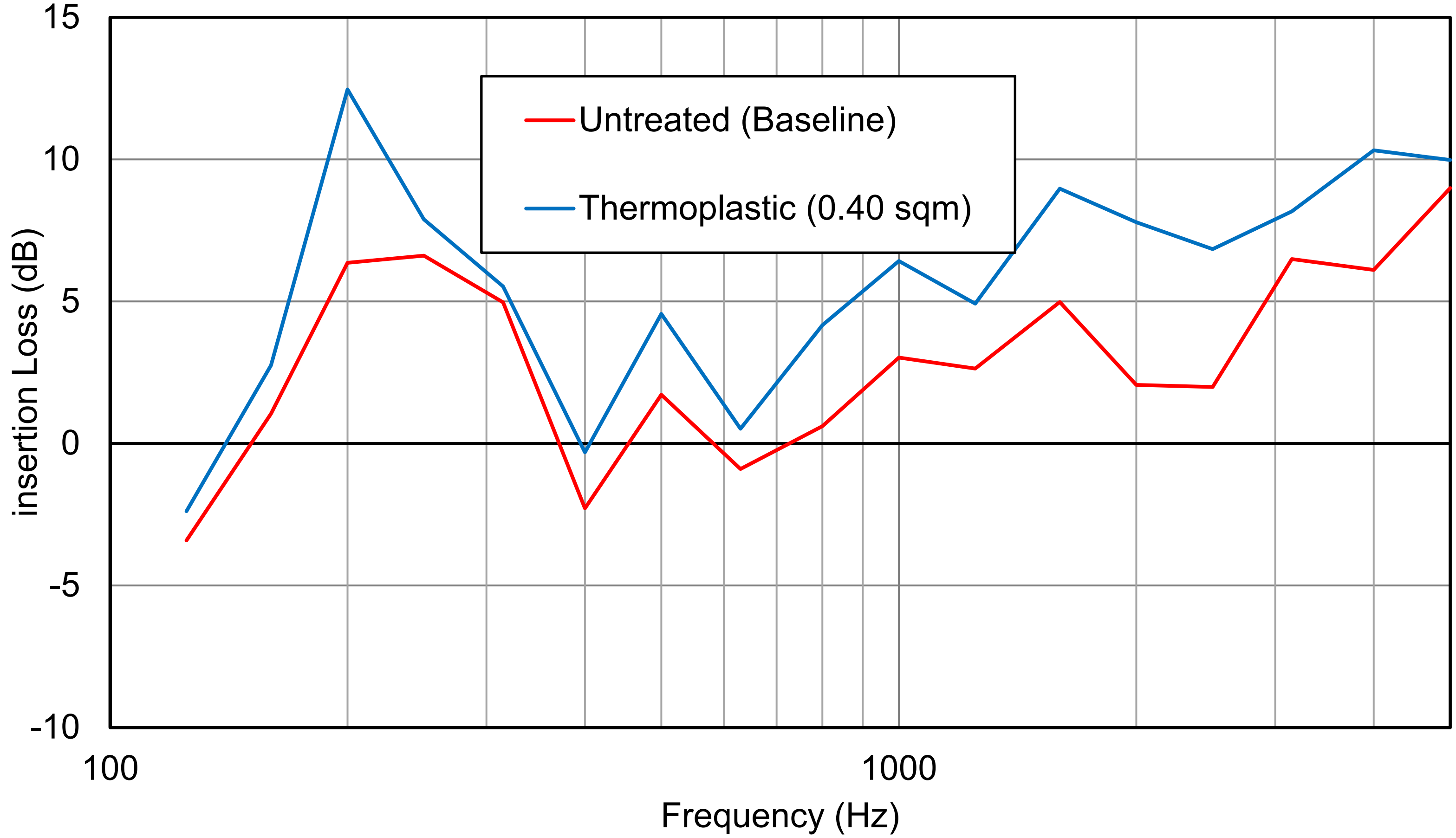
Reactive Absorbers Example





Thermoplastic Panel Absorber

Reactive Absorbers Example



Future Trends

- Hybrid dissipative – reactive sound absorbers
- 3D printed sound absorbers
- Microperforated panels
- Acoustic Fabrics